An Off-Axis Jet in Electromagnetic Counterparts to GW170817?

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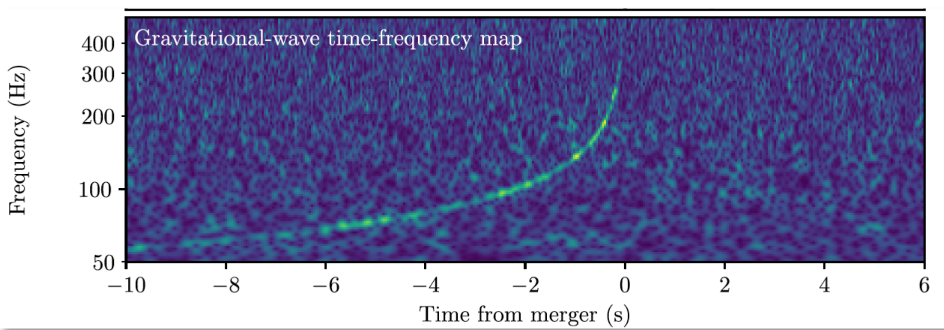
Multi-Messenger Era

21th Century: Multi-Messenger Era

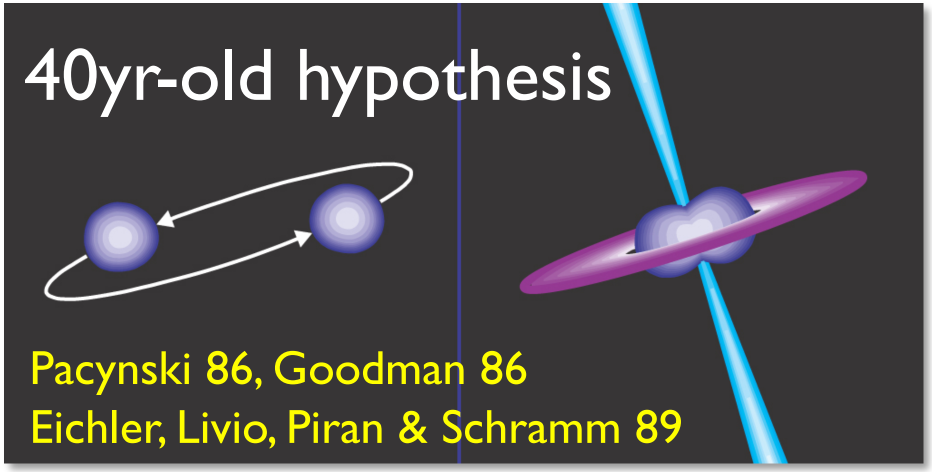
GW170817

1st GW from NS²



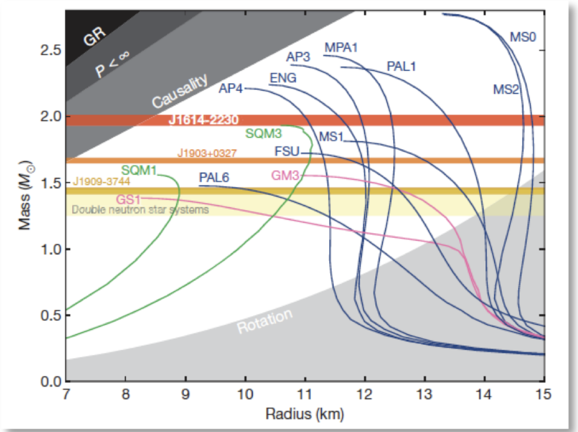
~100 sec chirp ⇒ NS-NS

NS² = Short GRB?

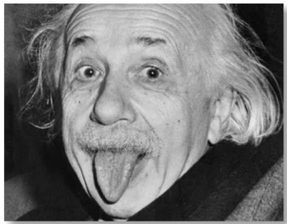


R-process elements

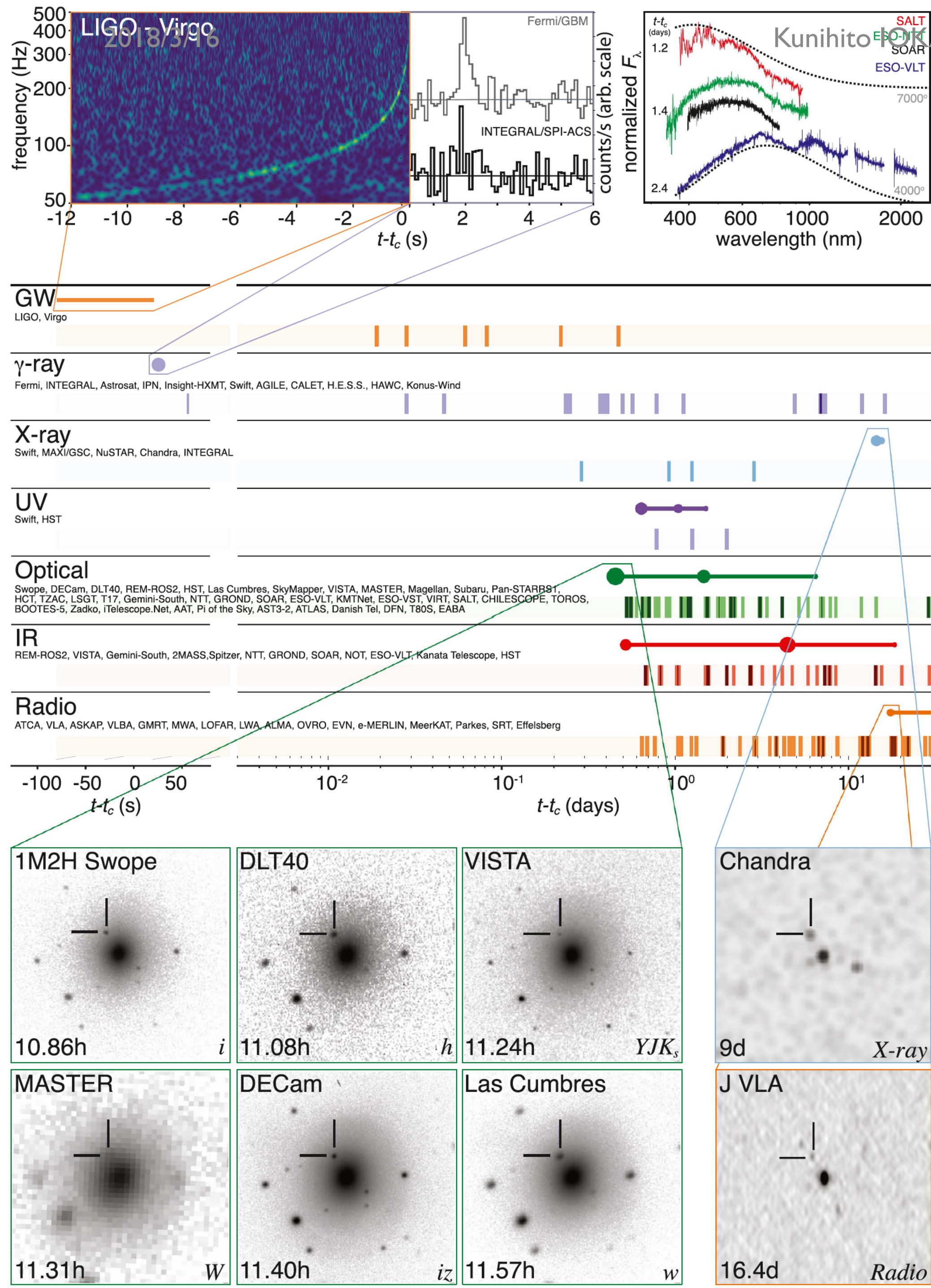
Equation of state



Relativity,
Cosmology,
…



New Era of Multi-Messenger



Follow-up observations

>3000 people

γ-ray: ~1.734±0.054 sec

⇒ sGRB 170817A

UV-Opt-IR: 10.86 hr

⇒ Macronova/Kilonova

X, radio: ~10 day

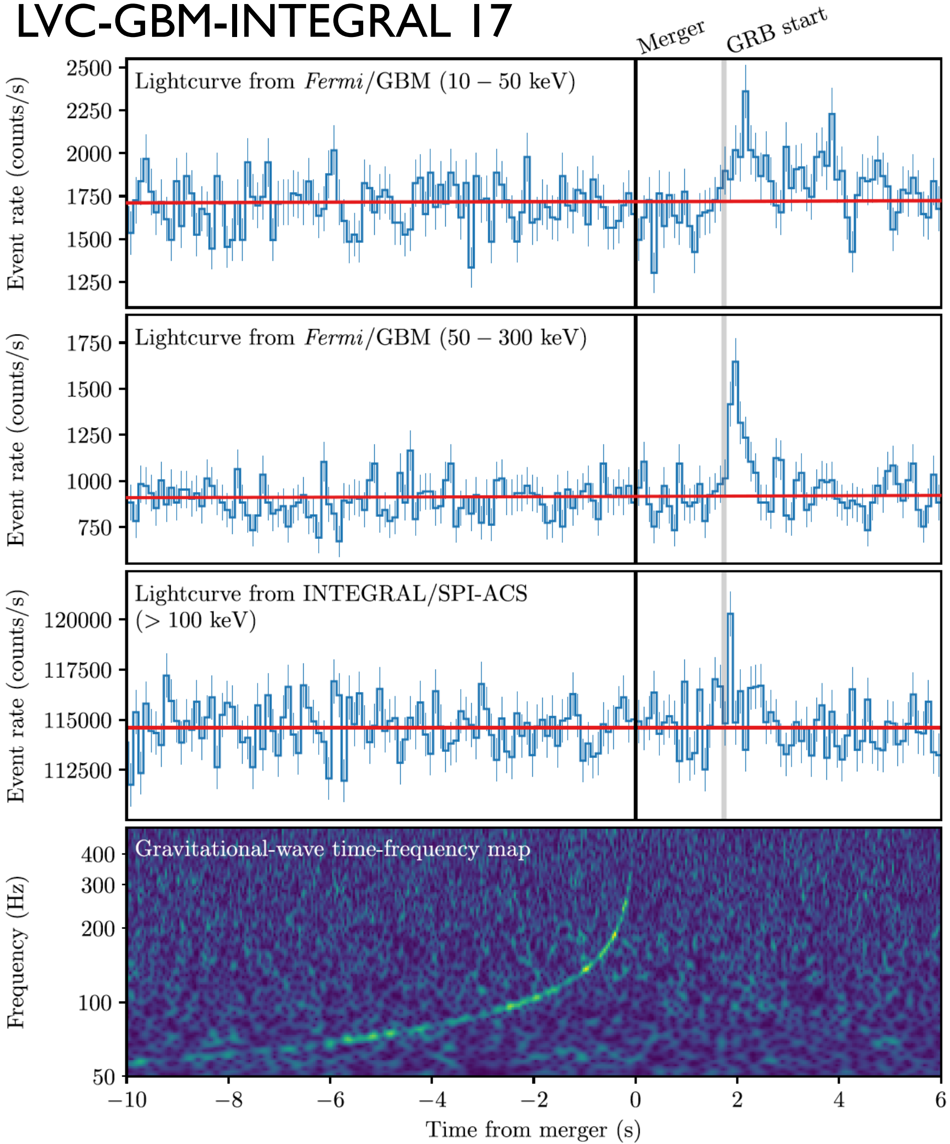
⇒ Afterglow

LVC-EM 17

Band: GCN circ., Circles ∝ brightness

GW170817 & GRB 170817A

LVC-GBM-INTEGRAL 17

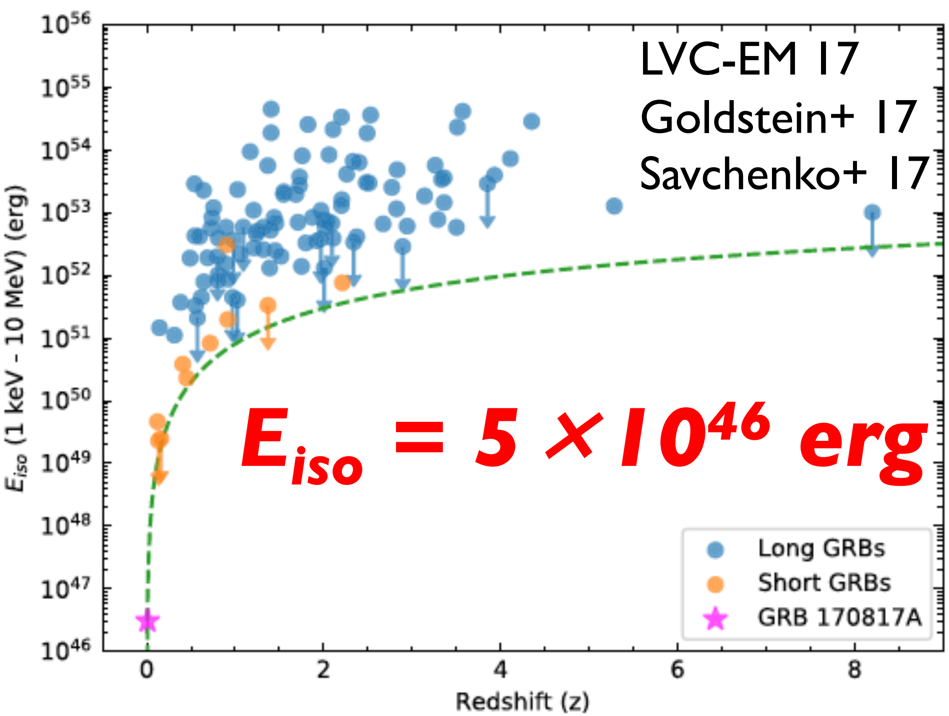


3 (of 12) GBM NaI detectors

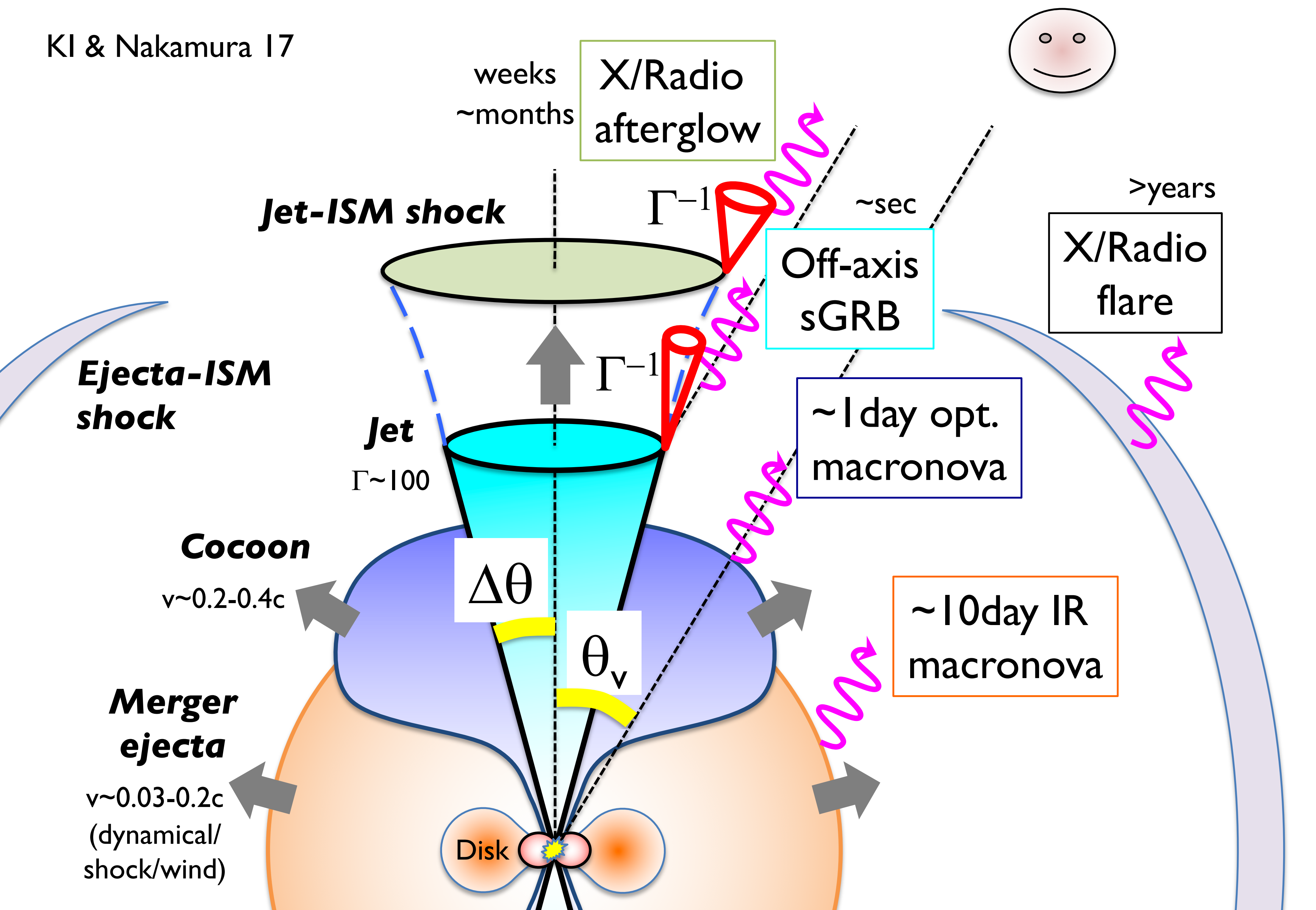
T_0=1.74±0.05 sec (68%)

T_{90}=2.0±0.5 sec

But very very weak



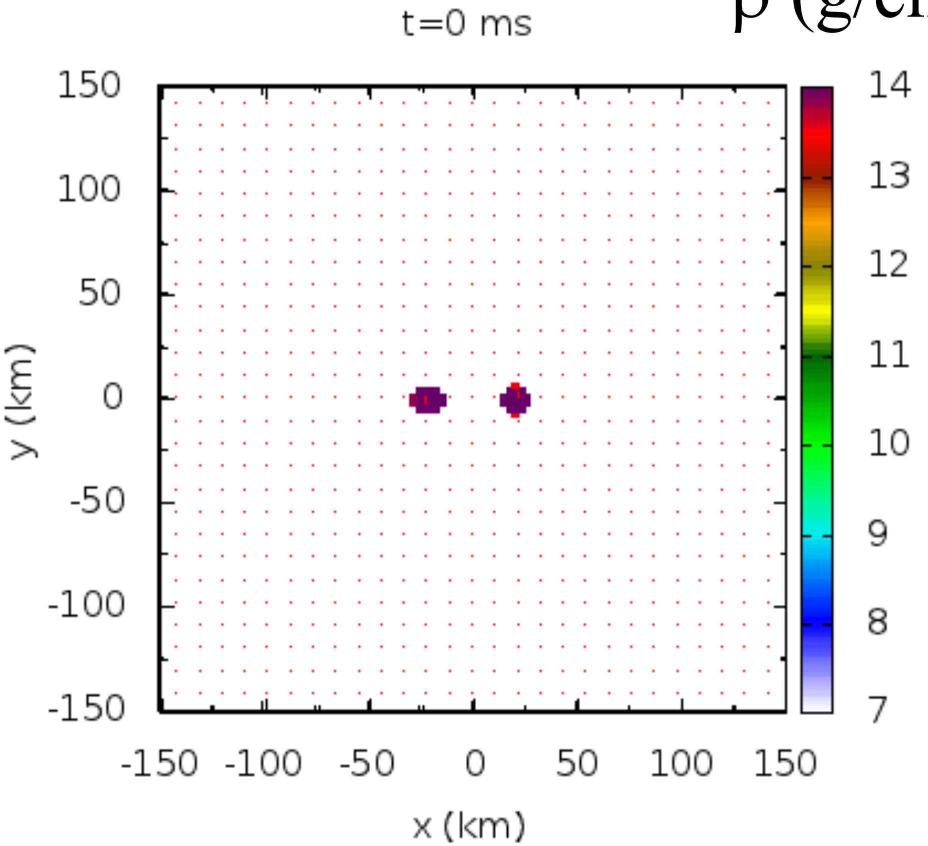
$E_{iso} = 5 \times 10^{46}$ erg

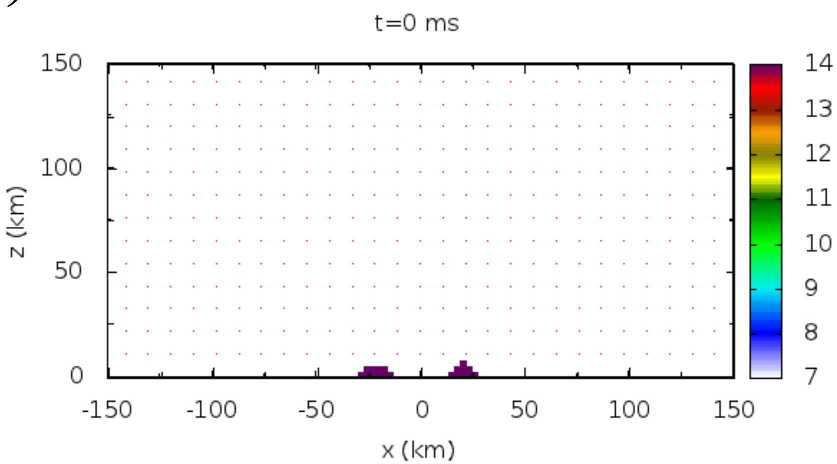

KI & Nakamura 17
weeks
~months
X/Radio
afterglow
Jet-ISM shock
Γ^{-1}
~sec
Off-axis
sGRB
>years
X/Radio
flare
Ejecta-ISM
shock
Jet
Γ^{-1}
Γ~100
~1day opt.
macronova
Cocoon
v~0.2-0.4c
$\Delta\theta$
θ_v
~10day IR
macronova
Merger
ejecta
v~0.03-0.2c
(dynamical/
shock/wind)
Disk

Merger of 1.3-1.4 M_{sun} NS:

EOS=APR4; stiff but relatively soft

ρ (g/cm³)

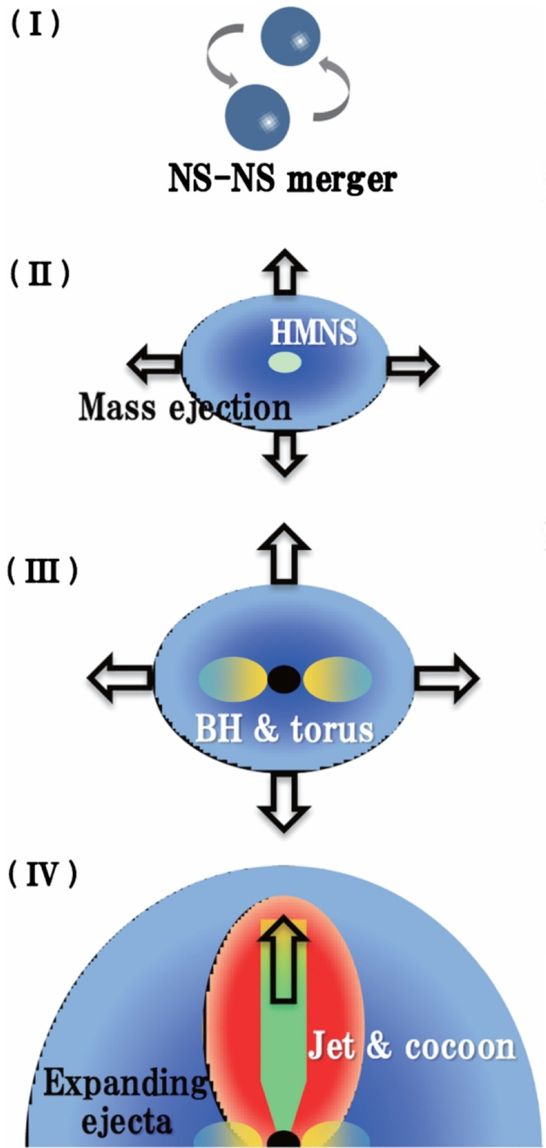




Relatively wider view

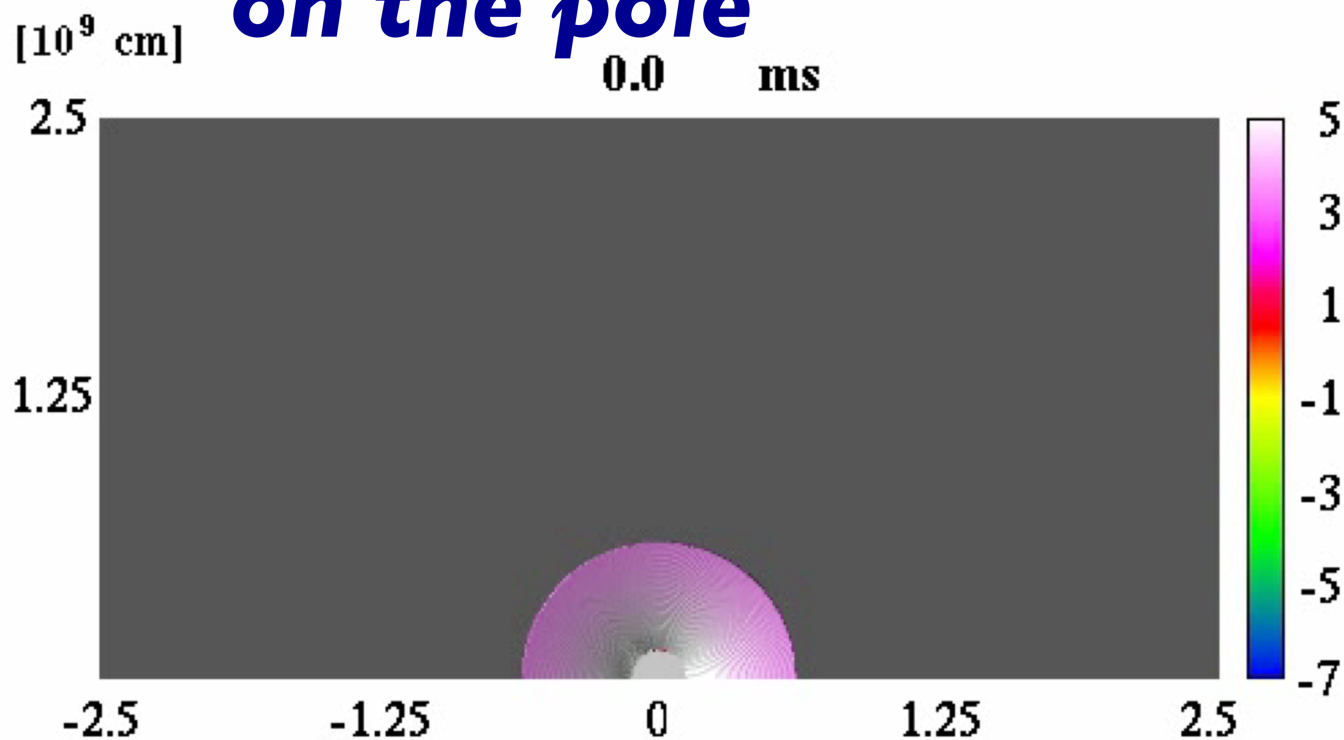
Orbital plane **_X-Z_ plane**

Jet Breakout from Ejecta



Ejecta is also on the pole

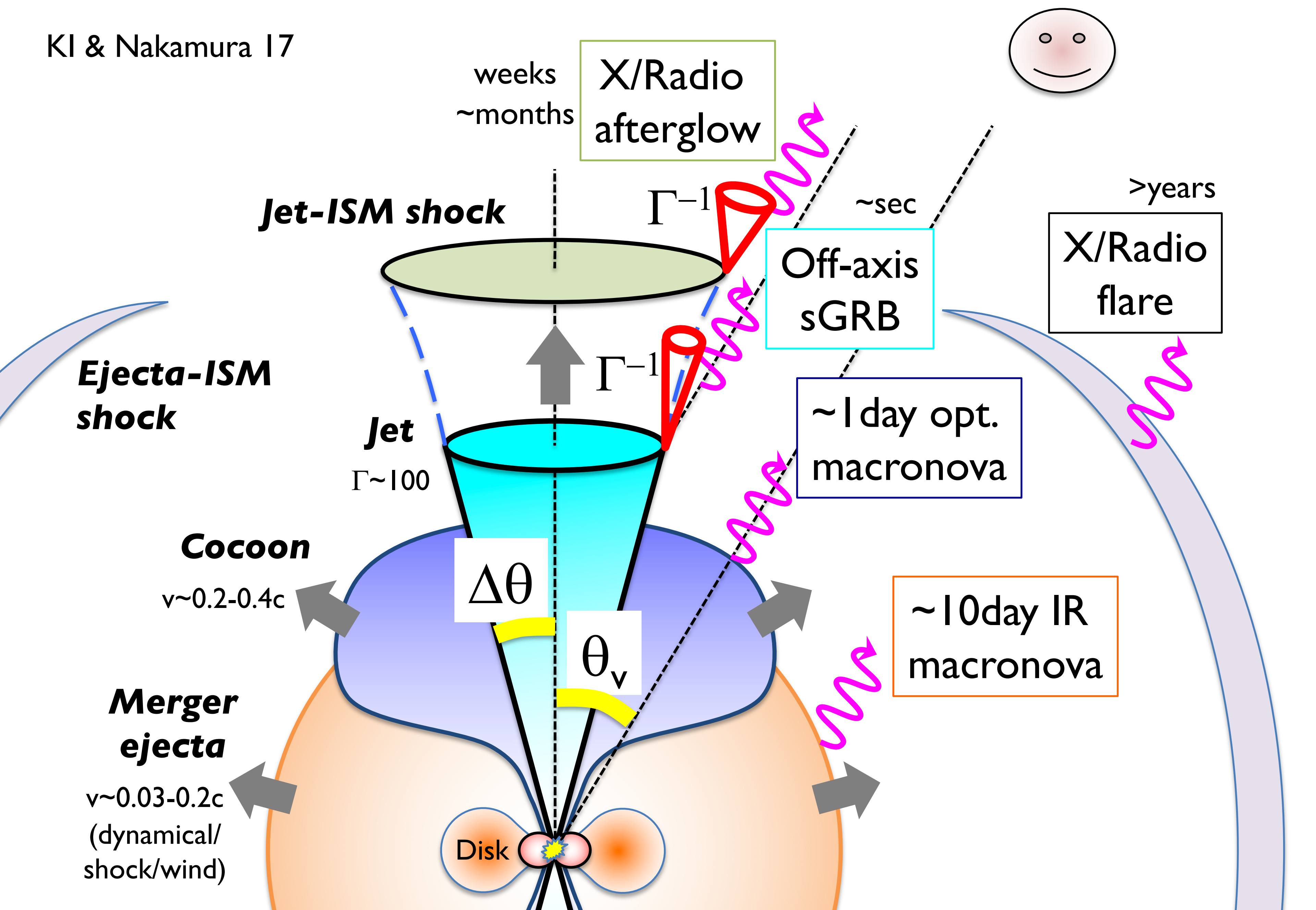
Nagakura+ 14
Murguia-Berthier + 14



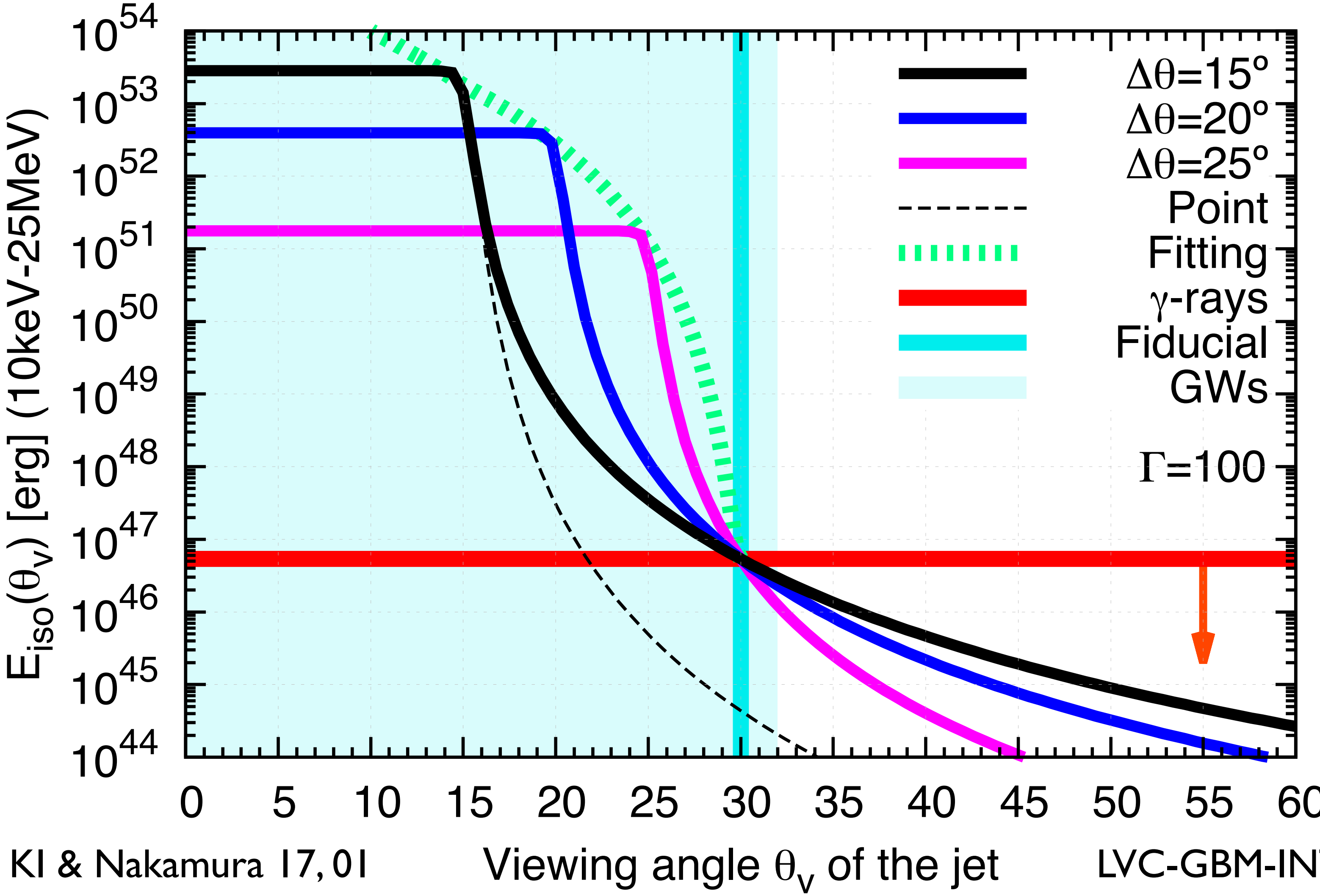
Similar to collapsars (long GRBs)

Weak jet $\sim 10^{46}$ erg/s cannot break out

KI & Nakamura 17



Off-Axis Jet



$\theta_v \sim \Delta\theta$ ⇒ Point approx. is bad

$E_{iso} \propto \theta_v^{-6}$
↓
$E_{iso} \propto \theta_v^{-4}$

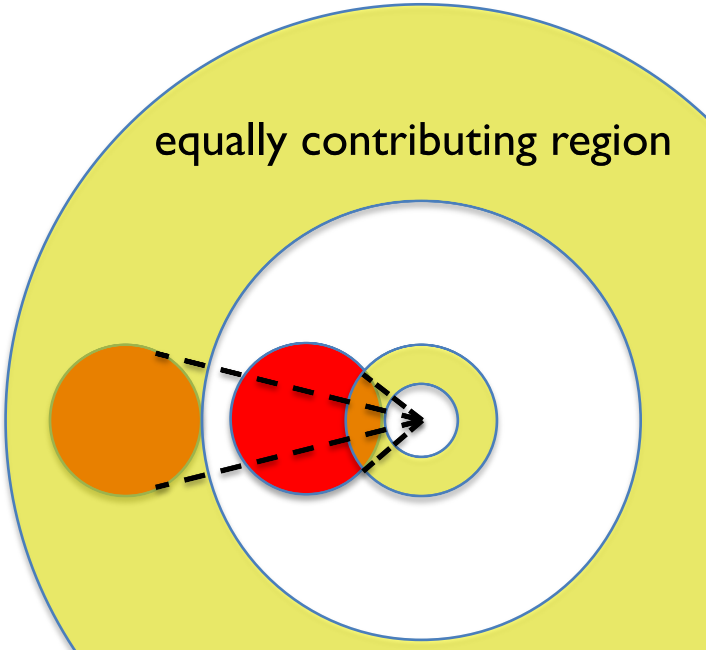
KI & Nakamura 17, 01
Yamazaki, KI & Nakamura 02, 03, 04

LVC-GBM-INTEGRAL 17
Granot+ 17, Kasliwal+ 17

Off-Axis E_{iso}

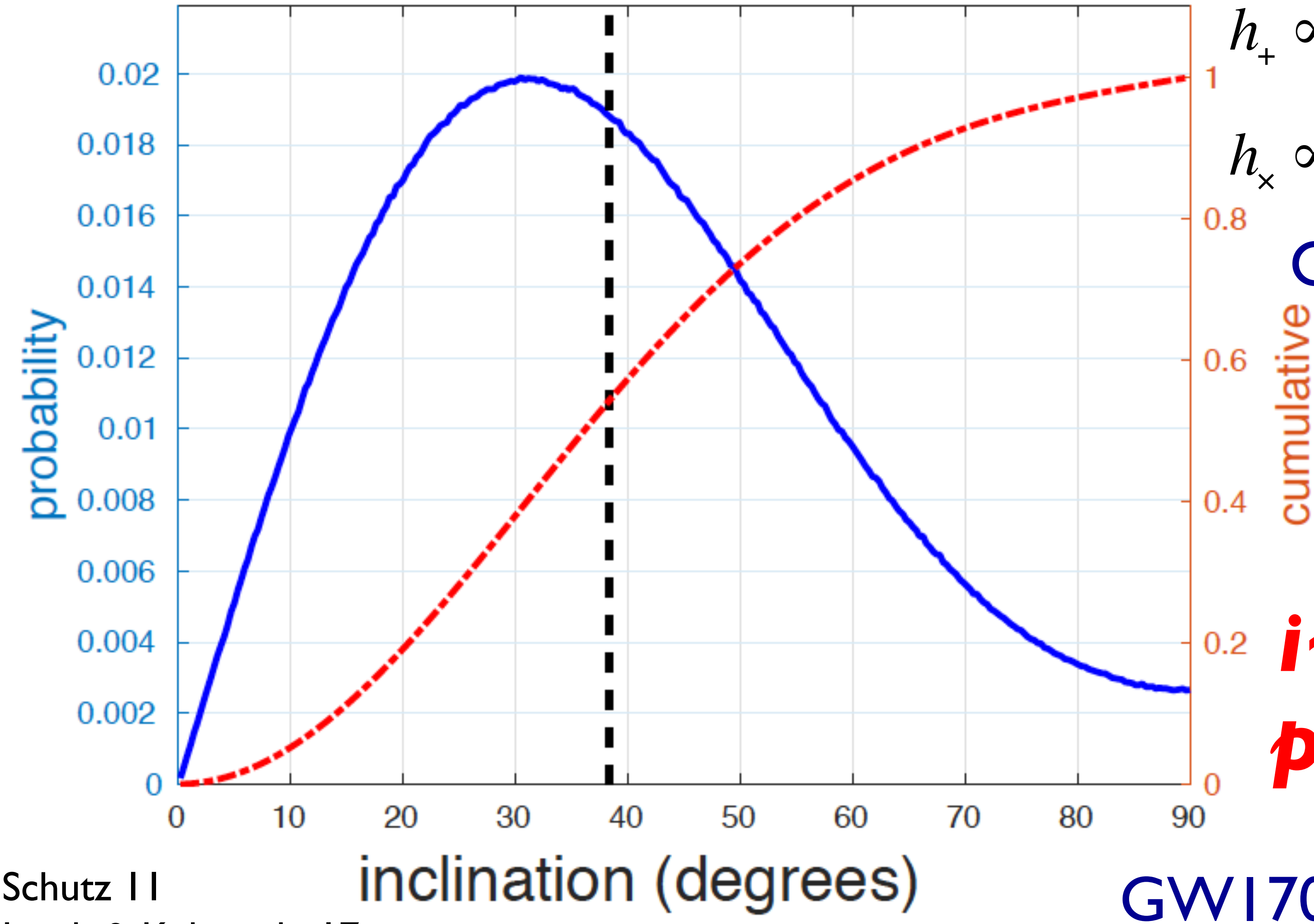
$$E_{\rm iso}(\theta_v) \propto {\rm const.} \quad {\rm for} \quad \theta_v < \Delta\theta,$$
$$E_{\rm iso}(\theta_v) \propto \tilde{\delta}(\theta_v)^2 \quad {\rm for} \quad \Delta\theta < \theta_v \lesssim 2\Delta\theta,$$
$$E_{\rm iso}(\theta_v) \propto \delta(\theta_v)^3 \quad {\rm for} \quad 2\Delta\theta \lesssim \theta_v.$$

$$\tilde{\delta}(\theta_v) \equiv \frac{1}{\Gamma[1-\beta\cos(\theta_v-\Delta\theta)]},$$
$$\delta(\theta_v) \equiv \frac{1}{\Gamma(1-\beta\cos\theta_v)}.$$



$\Delta\theta$: jet opening angle, θ_v: viewing angle

Viewing Angle Probability



$$h_+ \propto \frac{1}{2}\left(1+\cos^2 i\right)$$

$$h_\times \propto \cos i$$

On-axis GW is strong

i~30° is probable

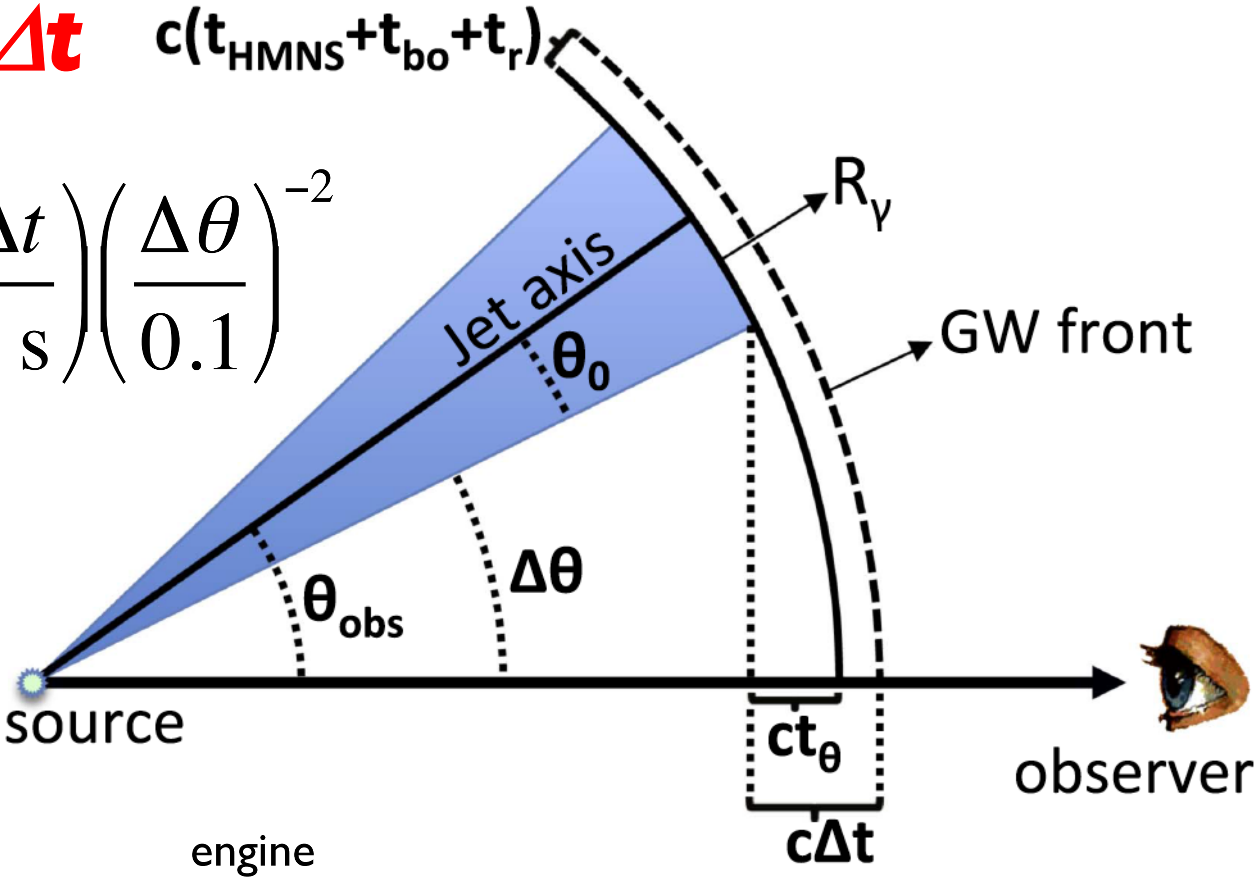
GW170817: i<~30°

Schutz 11
Lamb & Kobayashi 17

Time Scales

Time delay Δt

$$R_\gamma < 6\times10^{12}\,\mathrm{cm}\left(\frac{\Delta t}{1\ \mathrm{s}}\right)\left(\frac{\Delta\theta}{0.1}\right)^{-2}$$



Duration

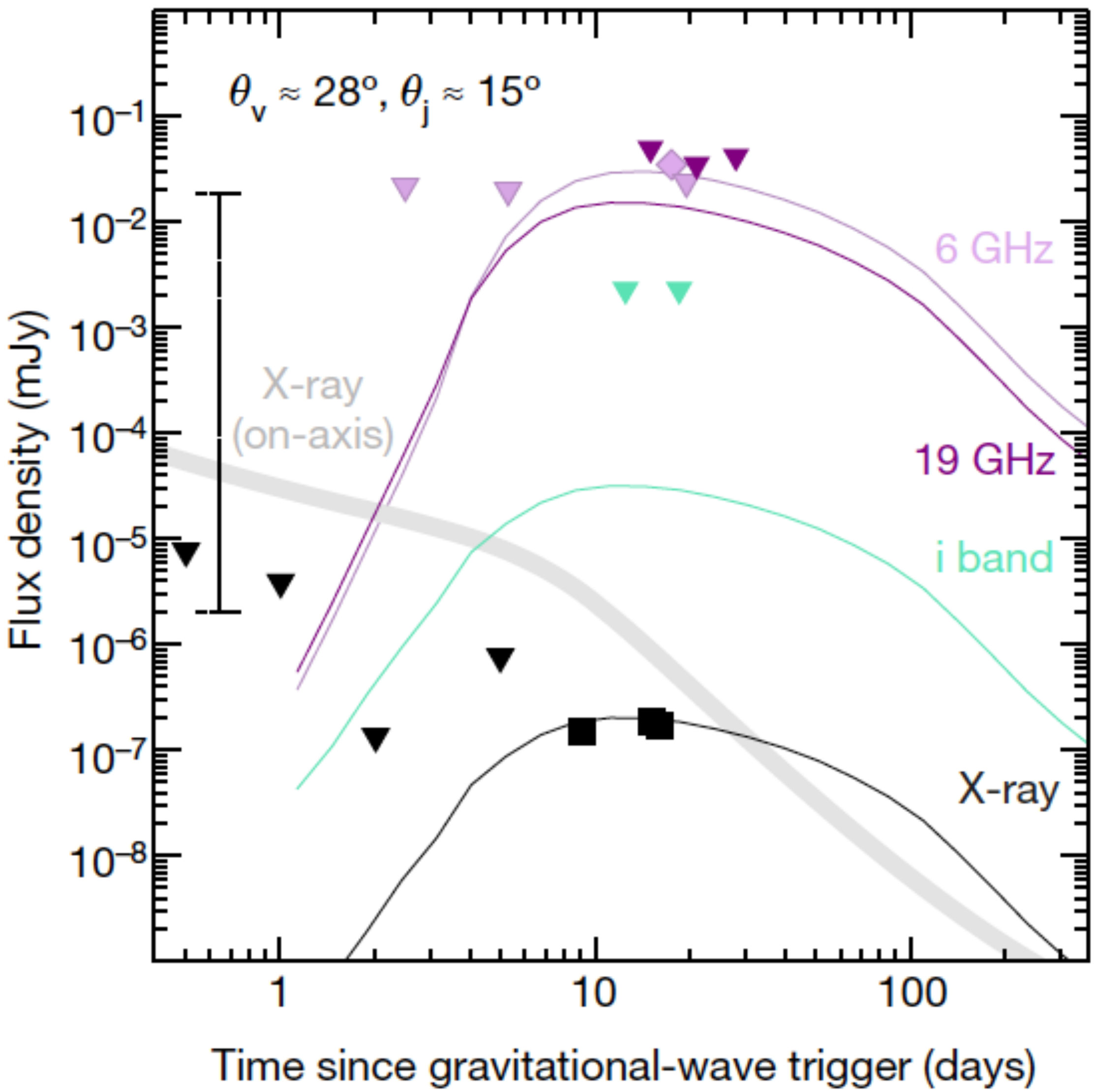
engine duration

$$T_{90} \sim \max\left[t_{\mathrm{dur}}, t_\theta\right]$$

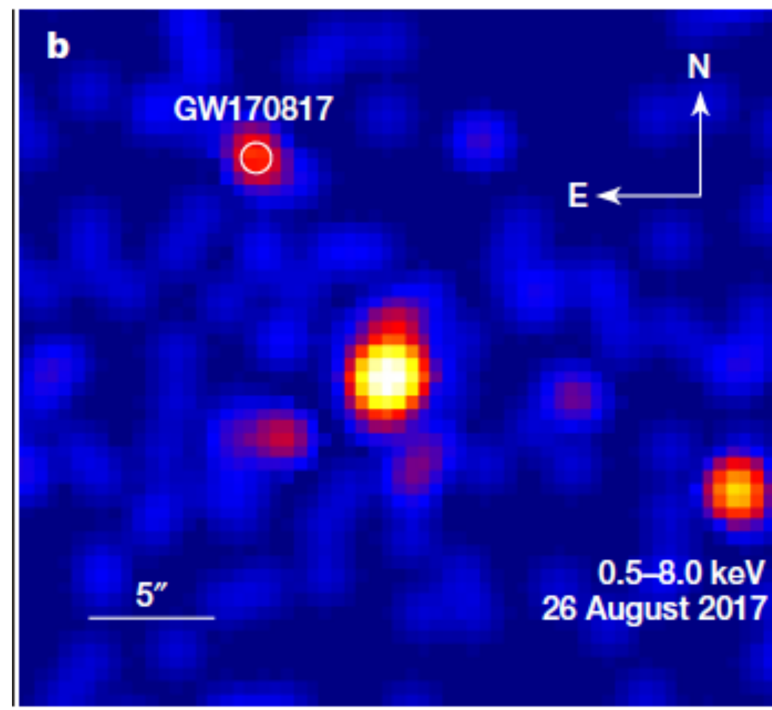
Granot+ 17
KI & Nakamura 17

Kasliwal+ 17
Gottlieb+ 17
Bromberg+ 17

X-ray Afterglow

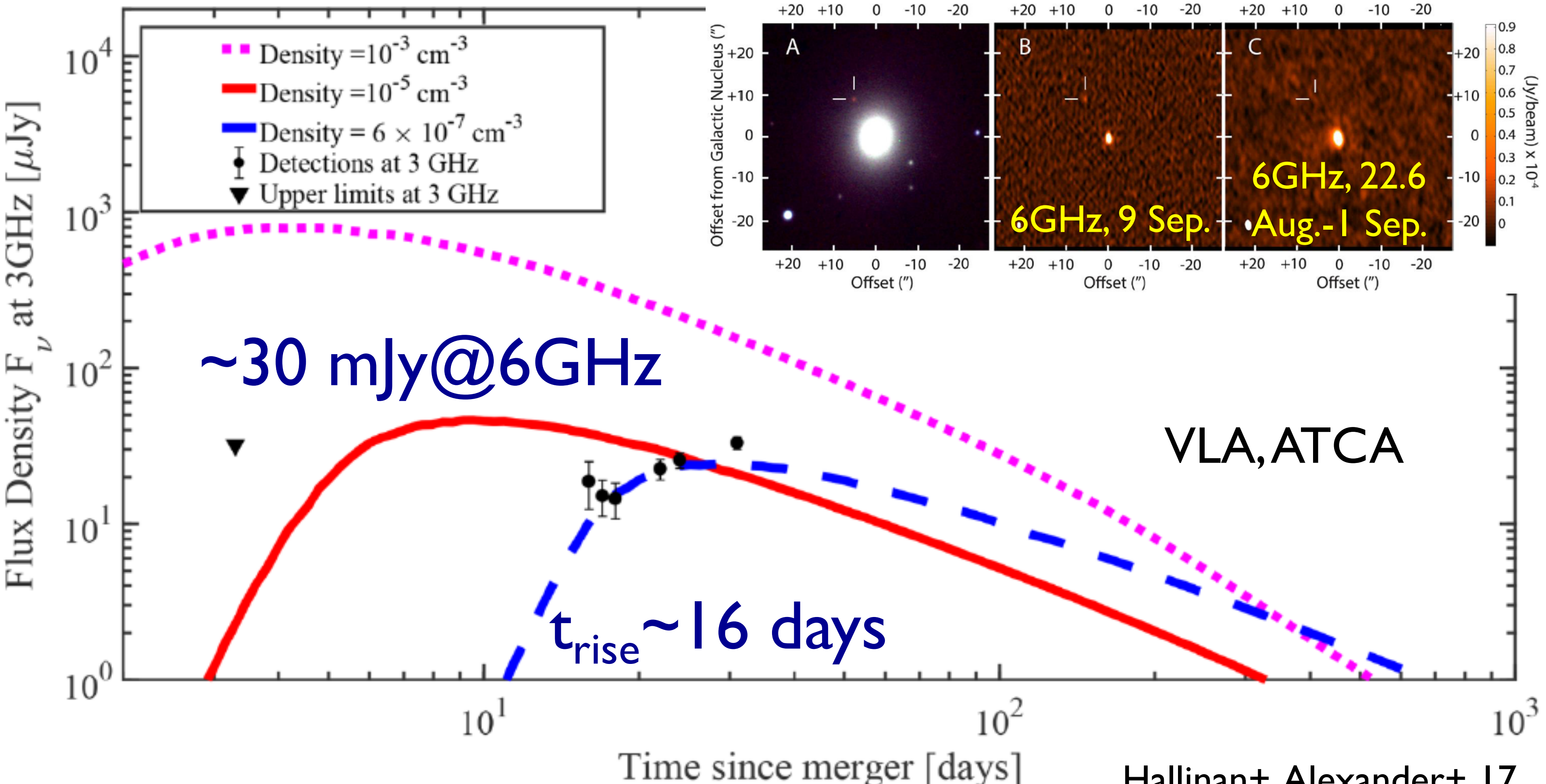


Chandra 50ks
t_{rise}~9 day
$L_{X,iso}$~1.1e39 erg/s



Troja+, Margutti+, Haggard+ 17

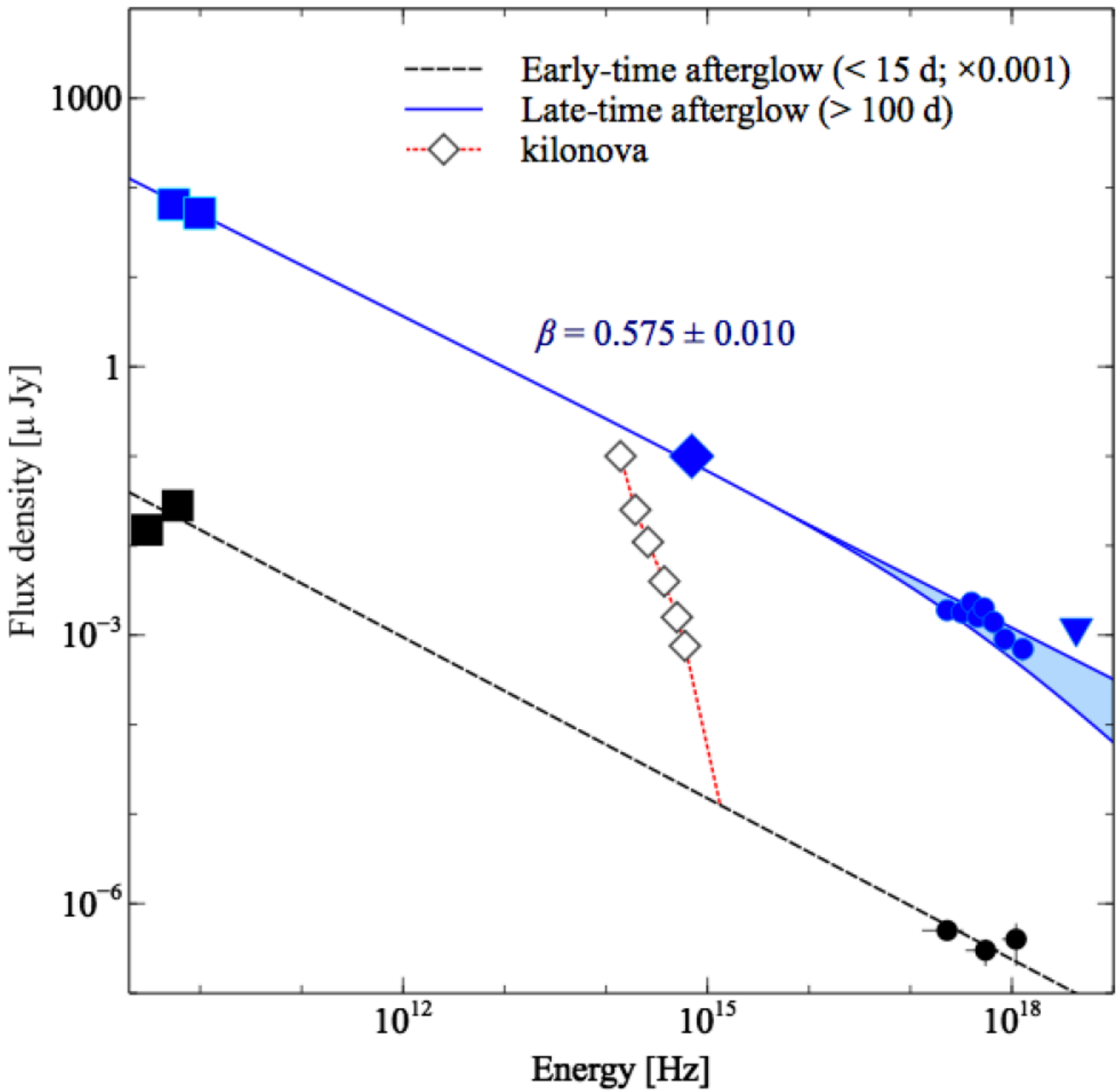
Radio Afterglow



Hallinan+, Alexander+ 17

X/Radio ratio ~ Synchrotron p=2.2 ($\nu_m<\nu<\nu_c$)

Afterglow Spectrum



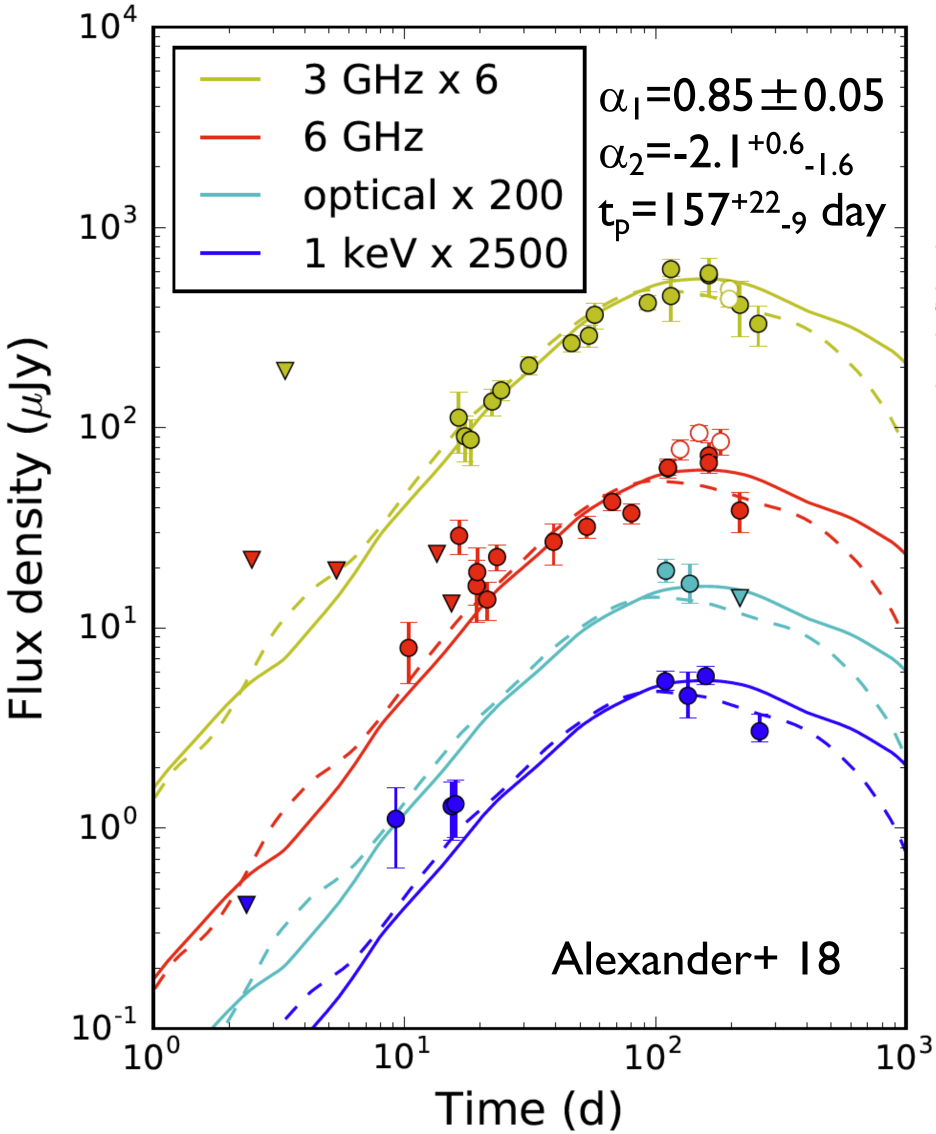
Consistent with a single power-law
⇒ Synchrotron
$\nu_m < \nu < \nu_c$

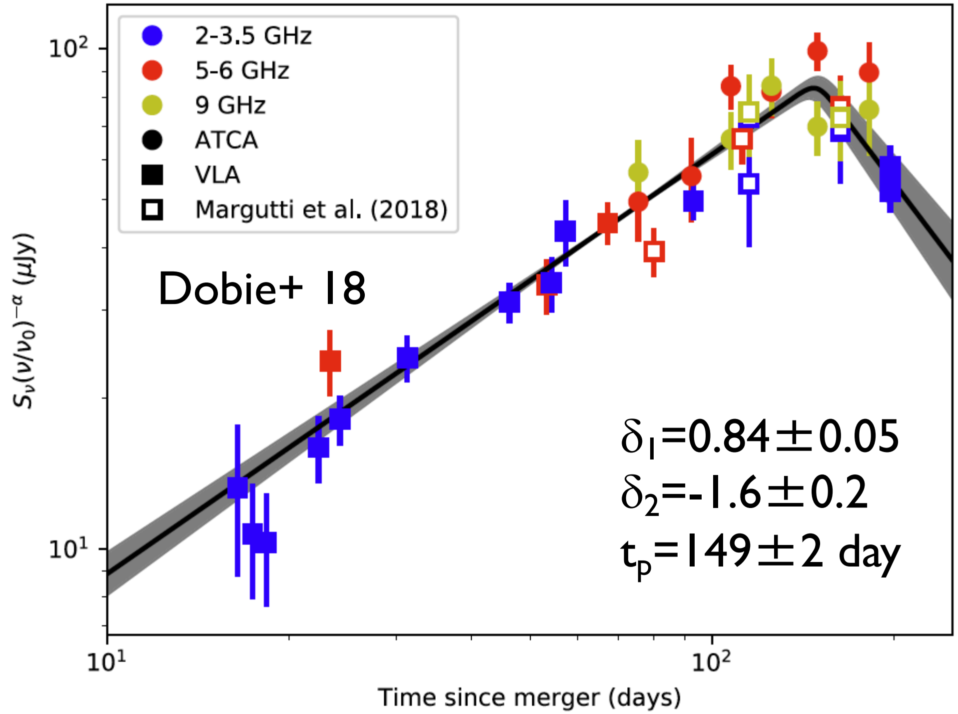
$F_\nu(t) \propto \nu^{0.6} t^{0.7}$

⇨ e spectrum:
$p \approx 2.2$

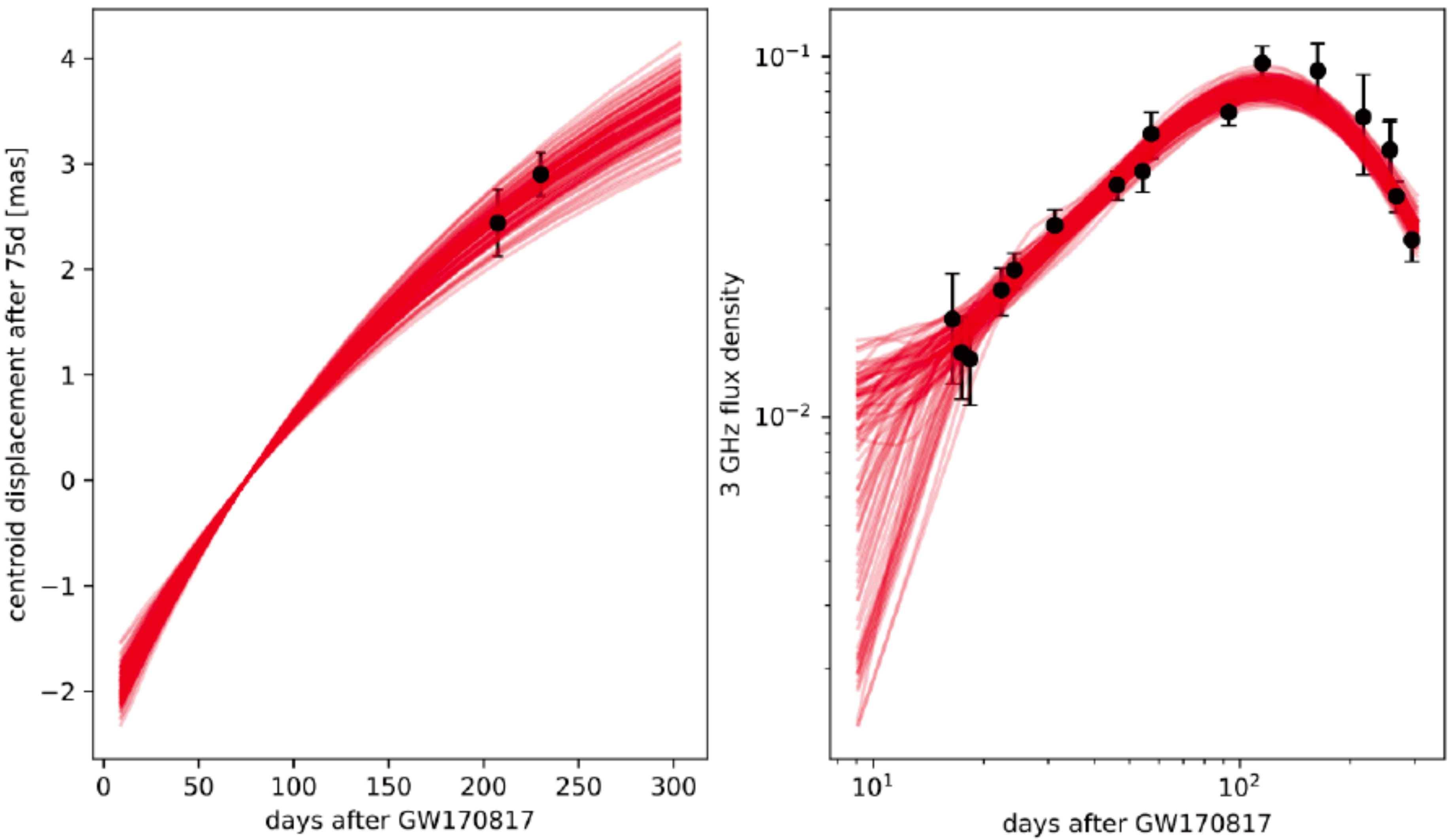
Troja+ 18, Marugutti+ 18, Ruan+ 18, D'Avanzo+ 18, Lyman+ 18,

Turnovers in Afterglows



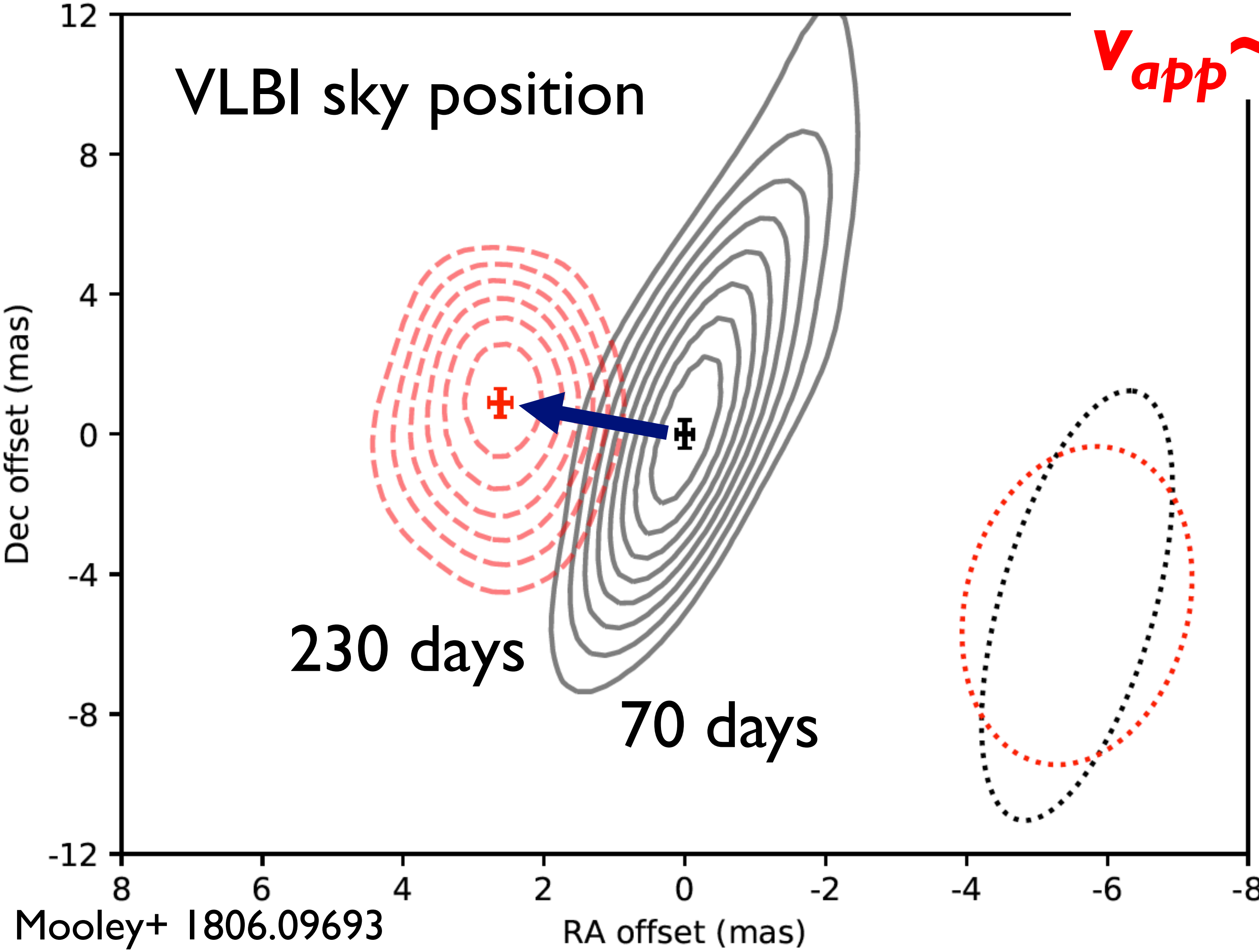


Sharp decline ⇒
Not a cocoon
Support a jet



Ghirlanda+ 18

Superluminal Motion



Mooley+ 1806.09693

v_{app}~4.1 ±0.5 c!

Unresolved

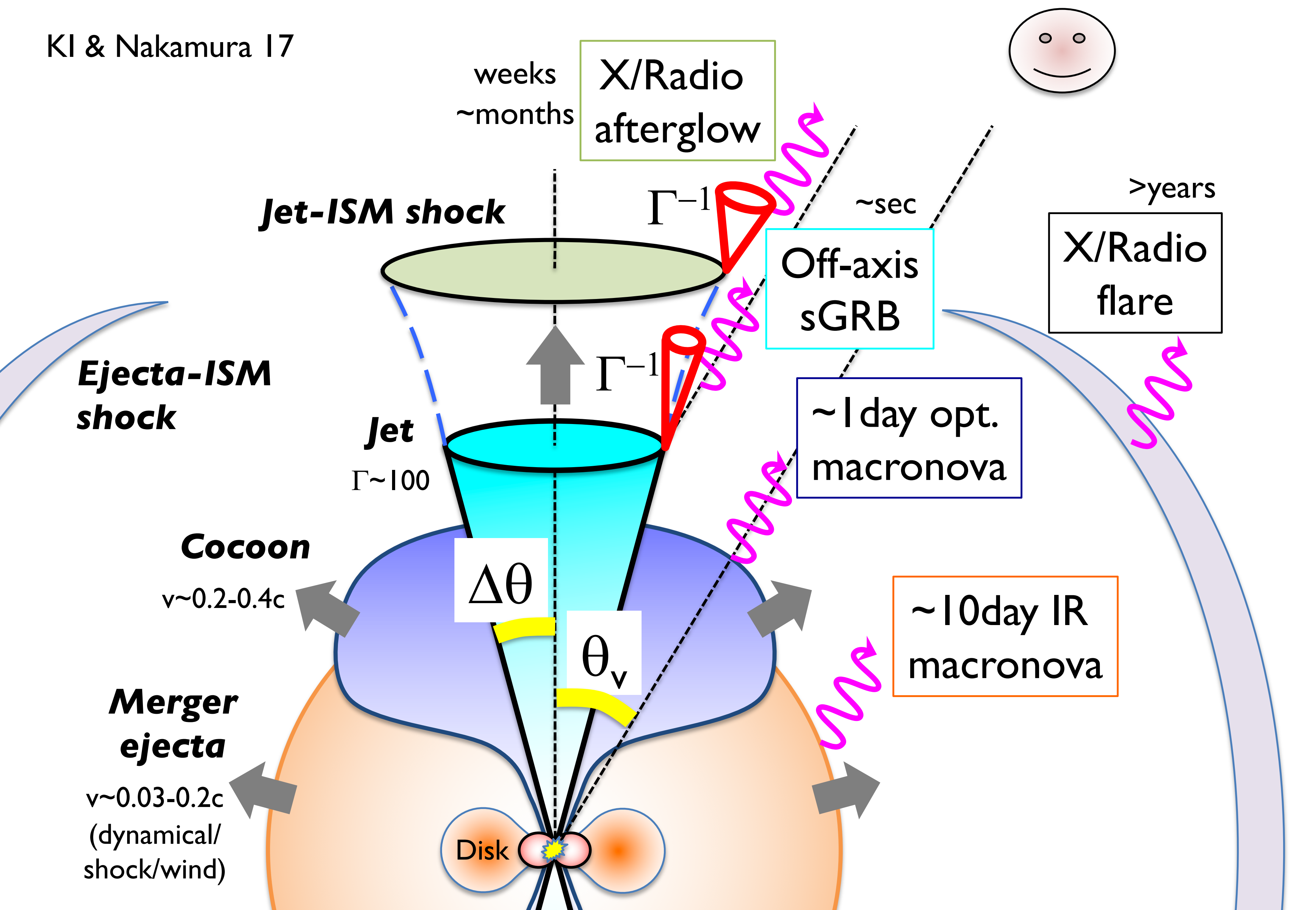
R<0.2pc(1mas), <2pc(10mas)

Not consistent with a spherical source

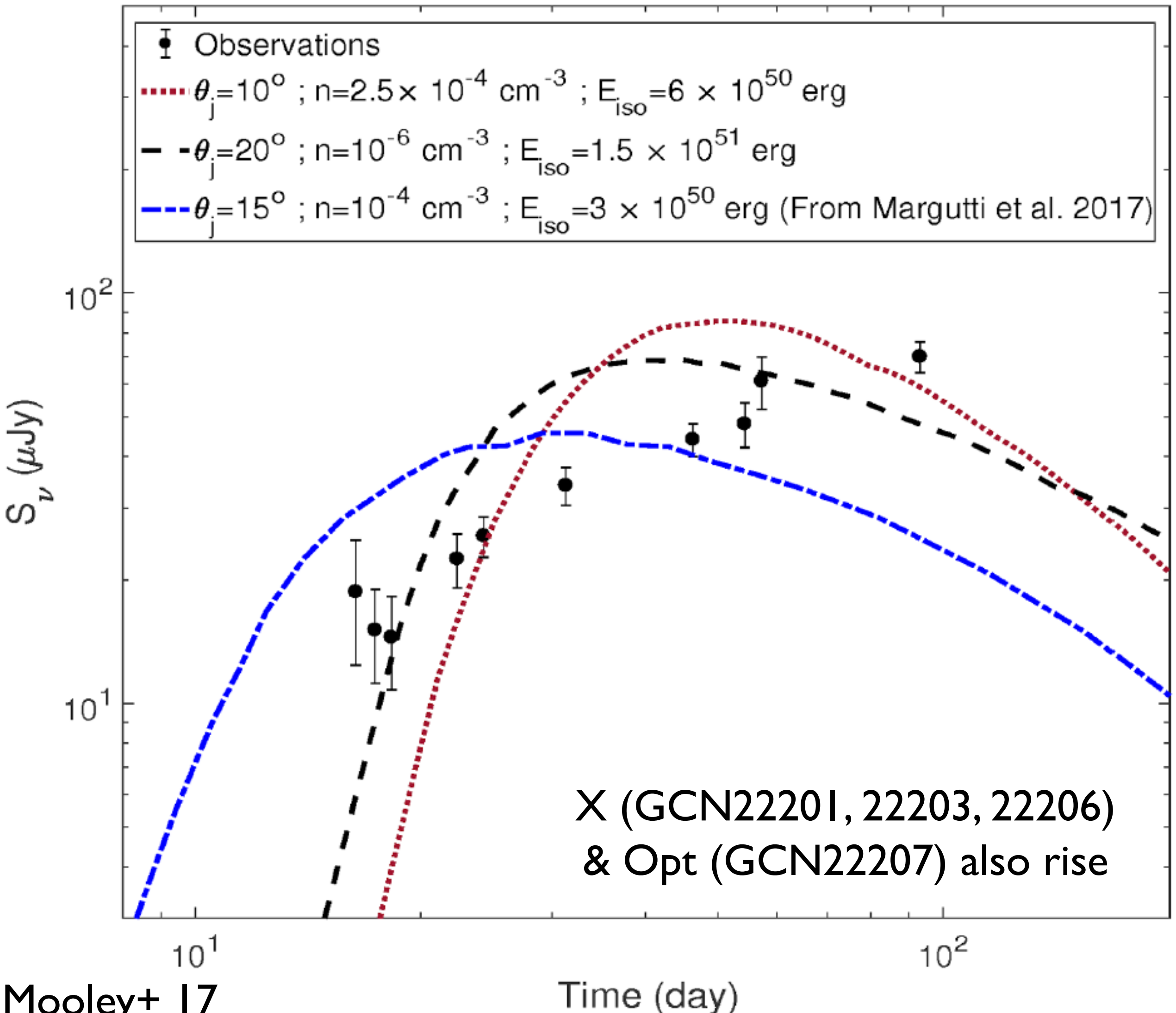
Γ~4

at t~t_{peak}

KI & Nakamura 17



Slowly Rising Afterglow



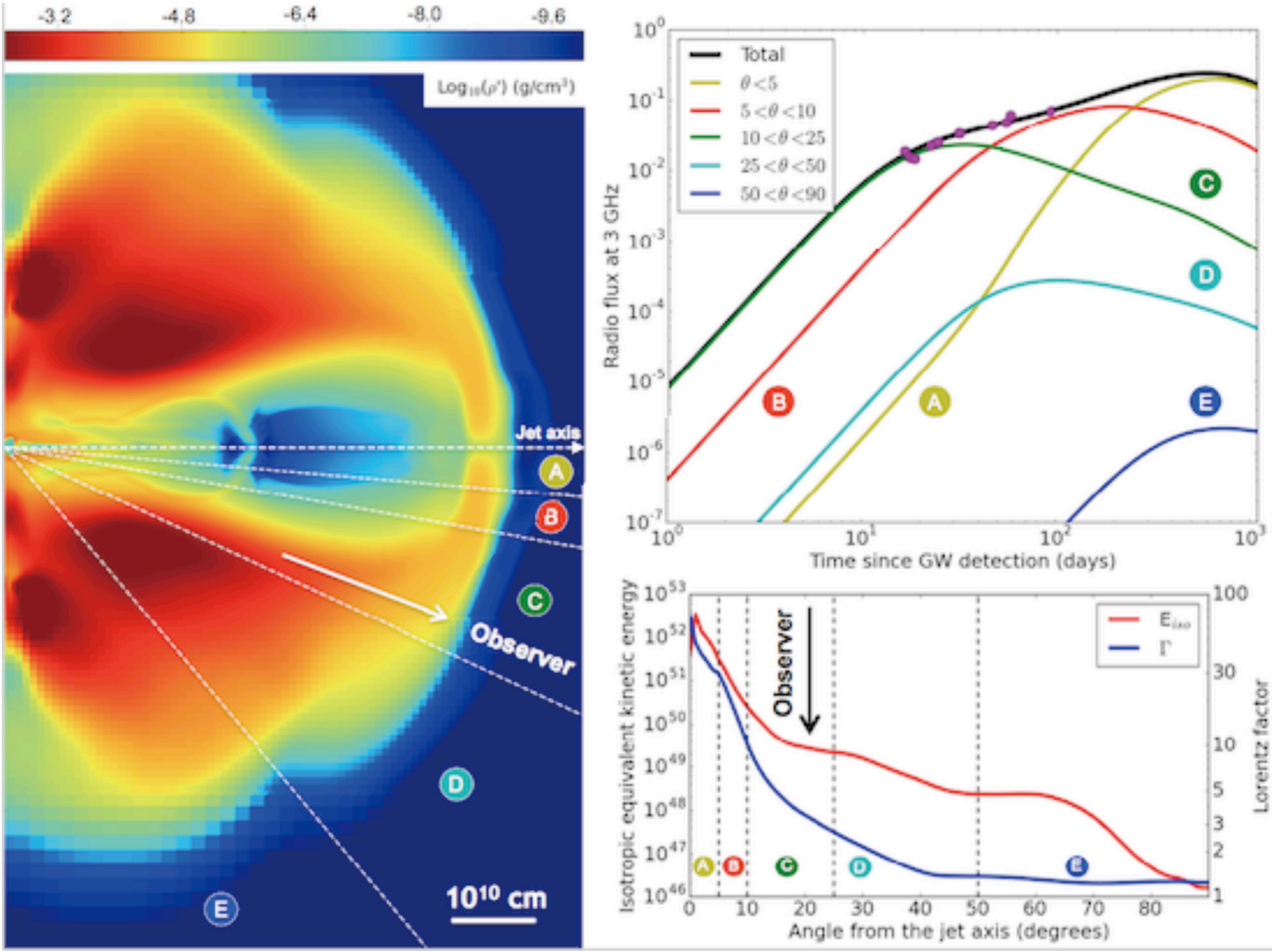
Mooley+ 17

Slowly rising up to ~100d

Inconsistent with a simple jet

Energy injection radial or polar: Structured jet or cocoon?

Structured Jet?



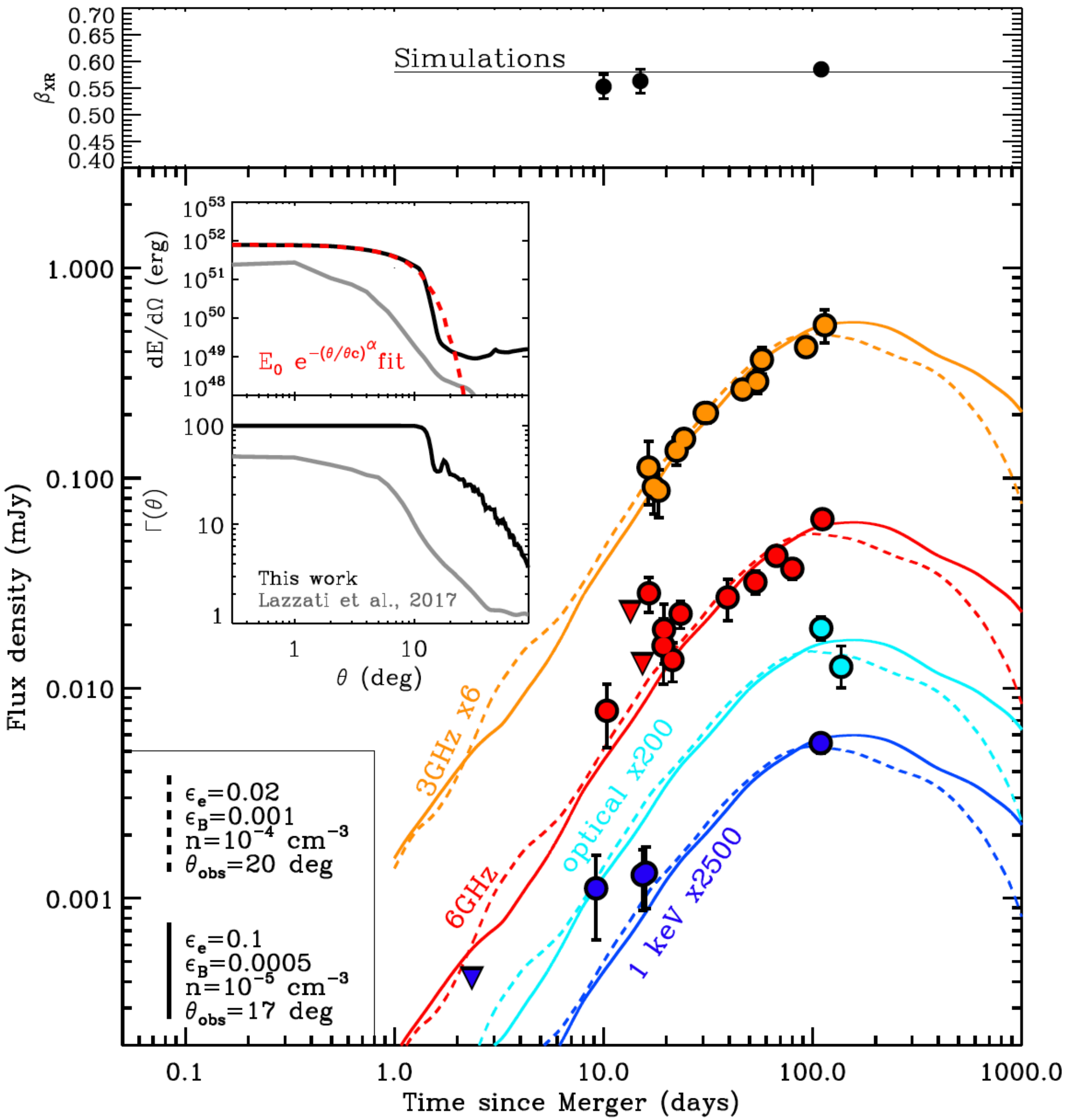
Polar energy injection

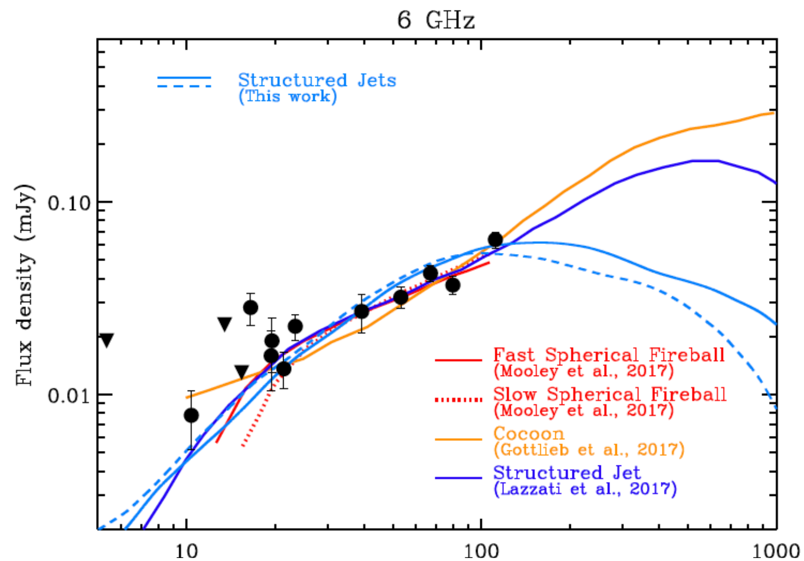
Jet+Coccon or Intrincially structured?

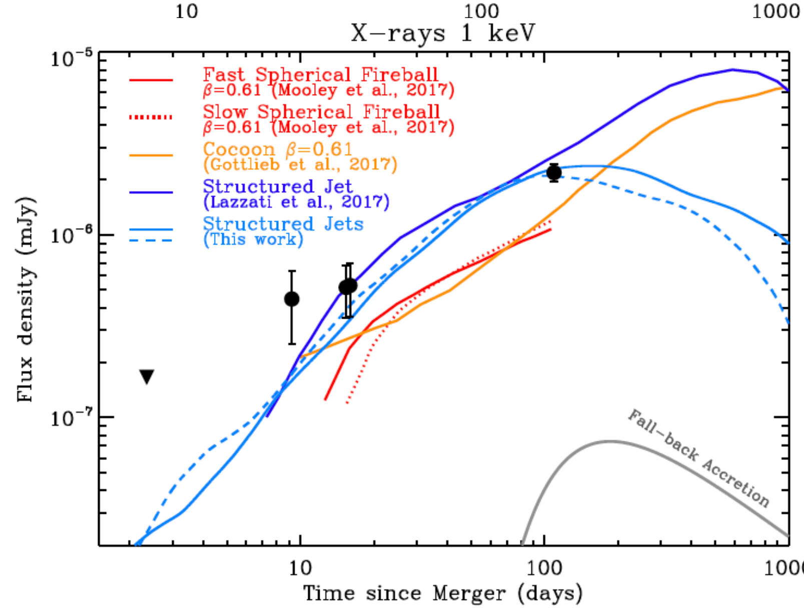
Lazzati+ 17

Marggutti+ 18
Lazzati+ 17
D'Avanzo+ 18
Lyman+ 18

Structured Jet?

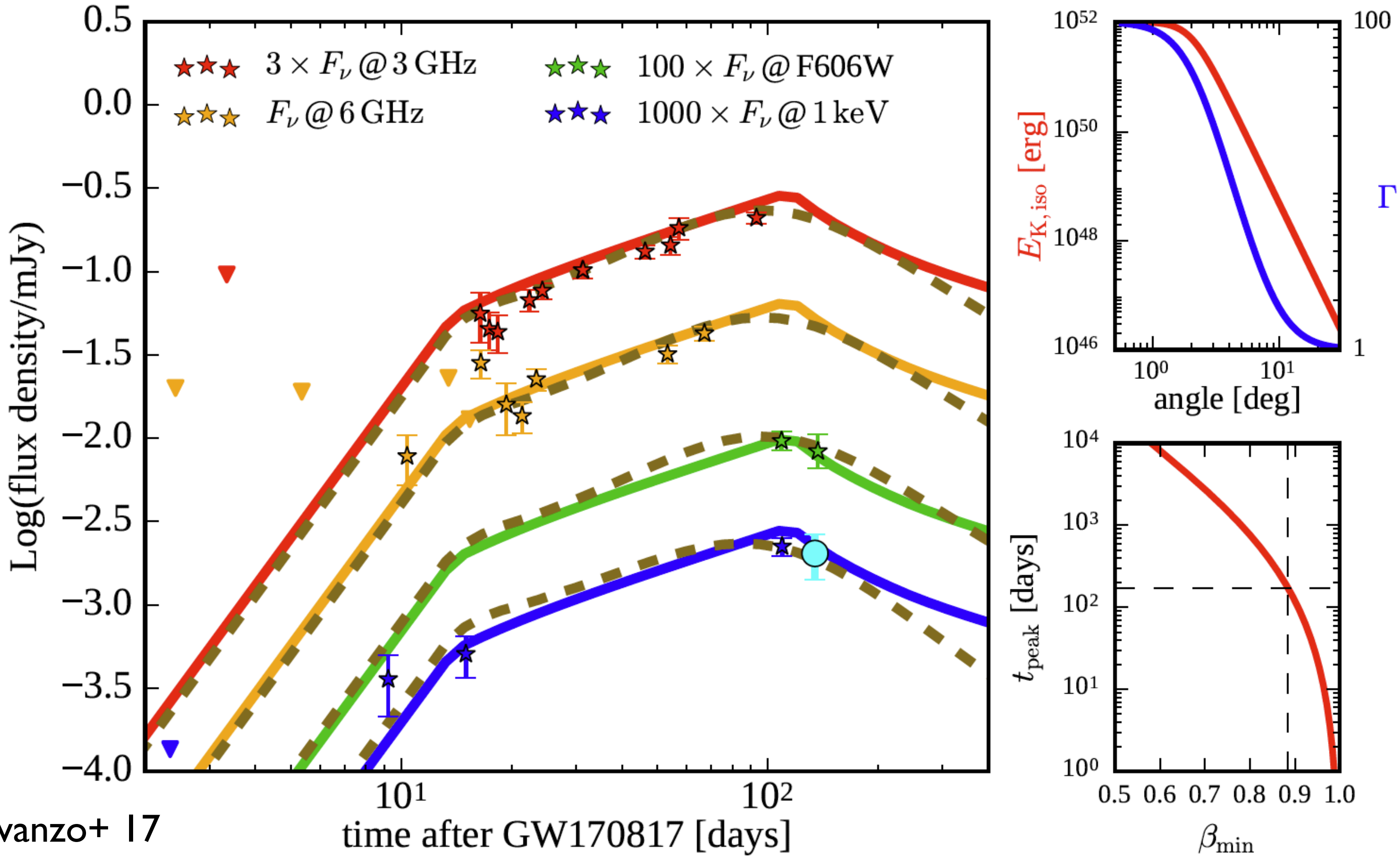






Power-Law Jet?

$F_\nu(t) \propto \nu^{0.6} t^{0.7}$ ⇨ e spectrum: $p \approx 2.2$



D'Avanzo+ 17

Gaussian Jet?

Troja+ 18

$$E(\theta) = E_0(-\theta^2/2\,\theta_c^2)$$

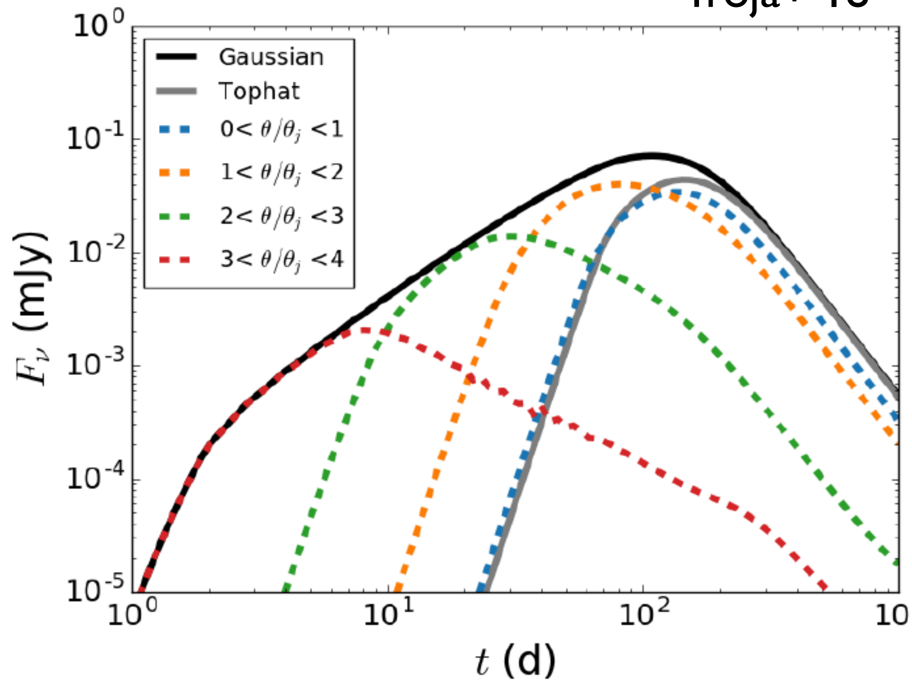


Table 2. Constraints on the Gaussian jet and Cocoon model param
distribution with symmetric 68% uncertainties (ie. the 16% and 84% q

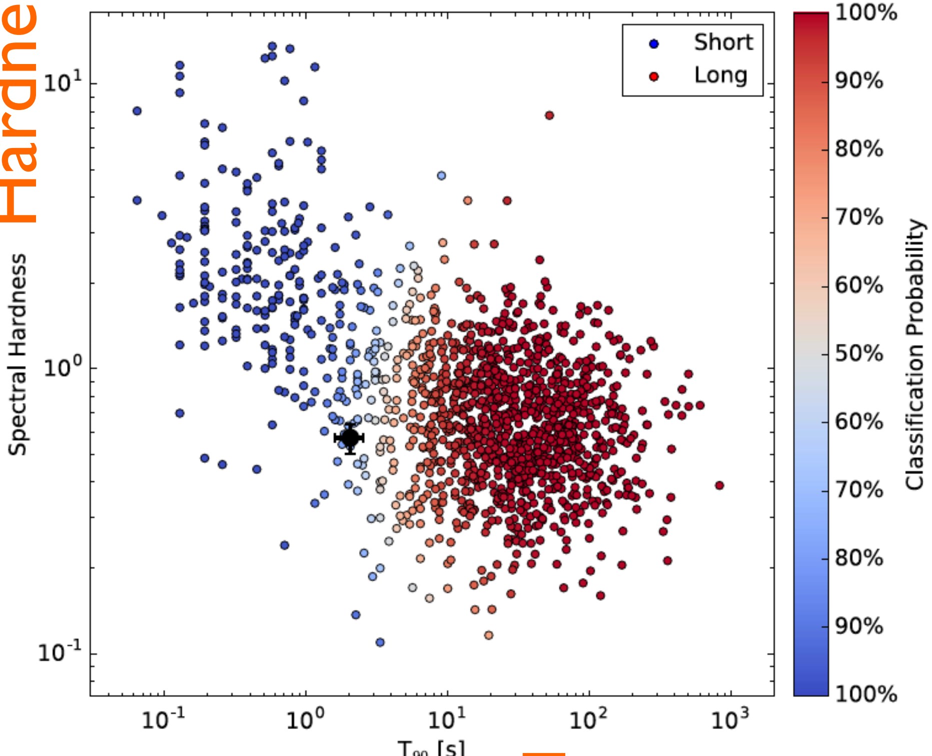
	Jet		Jet+GW+Planck			
Parameter	Med.	Best-fit	Med.	Best-fit		
θ_v	$0.51^{+0.20}_{-0.22}$	0.79	$0.32^{+0.13}_{-0.13}$	0.51		
$\log_{10} E_0$	$52.50^{+1.6}_{-0.79}$	54.39	$52.73^{+1.30}_{-0.75}$	56.93	$52.52^{+1.4}_{-0.71}$	56.93
θ_c	$0.091^{+0.037}_{-0.040}$	0.146	$0.057^{+0.025}_{-0.023}$	0.079	$0.076^{+0.026}_{-0.027}$	0.079
θ_w	$0.55^{+0.65}_{-0.22}$	0.63	$0.62^{+0.65}_{-0.37}$	0.44	$0.53^{+0.70}_{-0.24}$	0.44
$\log_{10} n_0$	$-3.1^{+1.0}_{-1.4}$	-3.8	$-3.8^{+1.0}_{-1.3}$	-6.4	$-3.24^{+0.91}_{-1.3}$	-6.4
p	$2.155^{+0.015}_{-0.014}$	2.159	$2.155^{+0.015}_{-0.014}$	2.170	$2.155^{+0.015}_{-0.014}$	2.170
$\log_{10} \epsilon_e$	$-1.22^{+0.45}_{-0.80}$	-0.73	$-1.51^{+0.53}_{-0.89}$	-1.37	$-1.31^{+0.46}_{-0.78}$	-1.37
$\log_{10} \epsilon_B$	$-3.38^{+0.81}_{-0.45}$	-3.50	$-3.20^{+0.92}_{-0.58}$	-1.27	$-3.33^{+0.82}_{-0.49}$	-1.27
$\log_{10} E_{tot}$	$50.26^{+1.7}_{-0.69}$	52.72	$50.16^{+1.1}_{-0.67}$	54.75	$50.19^{+1.41}_{-0.65}$	54.75

$\log_{10} u_{\rm min}$	$-2.2^{+1.9}_{-1.9}$	-2.9
$\log_{10} E_{\rm inj}$	$54.7^{+1.6}_{-2.7}$	52.4
k	$5.62^{+0.93}_{-1.1}$	5.3
$\log_{10} M_{\rm ej}$	$-7.6^{2.1}_{-1.7}$	-9.5
$\log_{10} n_0$	$-5.2^{+2.2}_{-2.0}$	-6.5
p	$2.156^{+0.014}_{-0.014}$	2.157
$\log_{10} \epsilon_e$	$-1.33^{+0.93}_{-1.3}$	-0.36
$\log_{10} \epsilon_B$	$-2.5^{+1.5}_{-1.1}$	-0.4
$\log_{10} E^*_{tot}$	$52.84^{+0.97}_{-1.3}$	51.00

Spectrum

$$E_p(\theta_v) \sim \left[\frac{\tilde{\delta}(\theta_v)}{\tilde{\delta}(0)}\right] E_p(0) \sim 10\,\mathrm{keV} \left[\frac{\Gamma(\theta_v - \Delta\theta)}{10}\right]^{-2} \left[\frac{E_p(0)}{\mathrm{MeV}}\right],$$

Hardness



Goldstein+ 17 (b) T_{90}

Main pulse

power law (a=-0.62±0.40)

+ cutoff (E_{peak}=185±62keV)

Weak tail

34% the fluence

of the main pulse

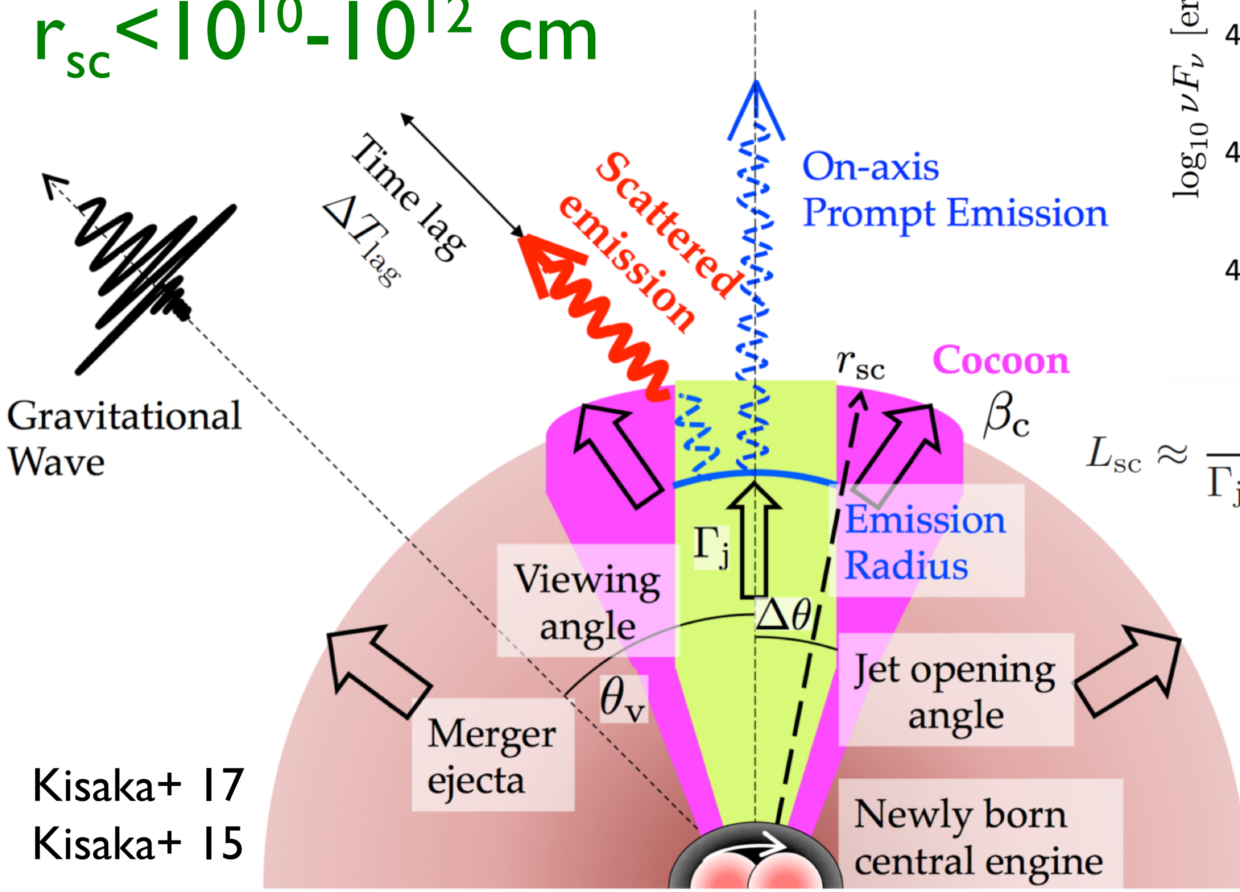
kT=10.3±1.5keV

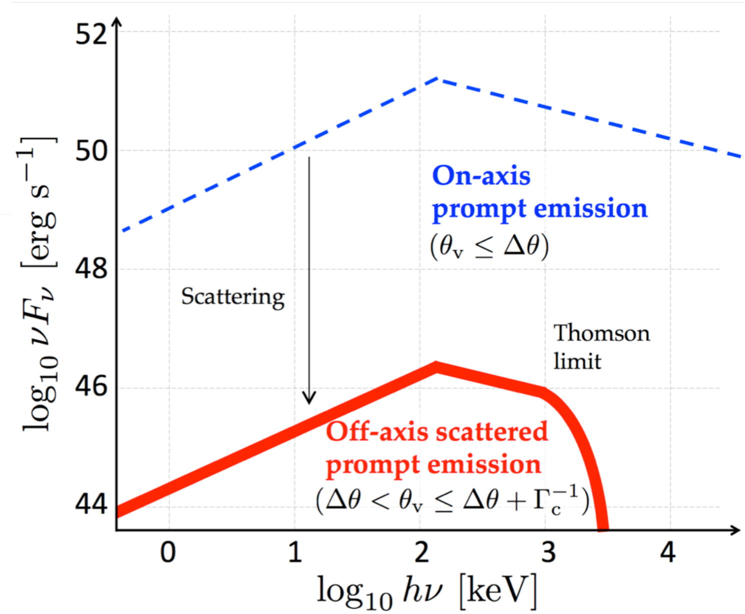
Scattered sGRB

Thompson scattering by cocoon

Copy spectrum w/ ~MeV cutoff

$r_{sc} < 10^{10}$-10^{12} cm





$$L_{sc} \approx \frac{2}{\Gamma_j \Delta\theta} \times \frac{t_{dur}}{T_{dur,sc}} \times \Gamma_c^2 \times \epsilon_{sc} \times \frac{\Delta\theta^2}{2} L_{iso}$$

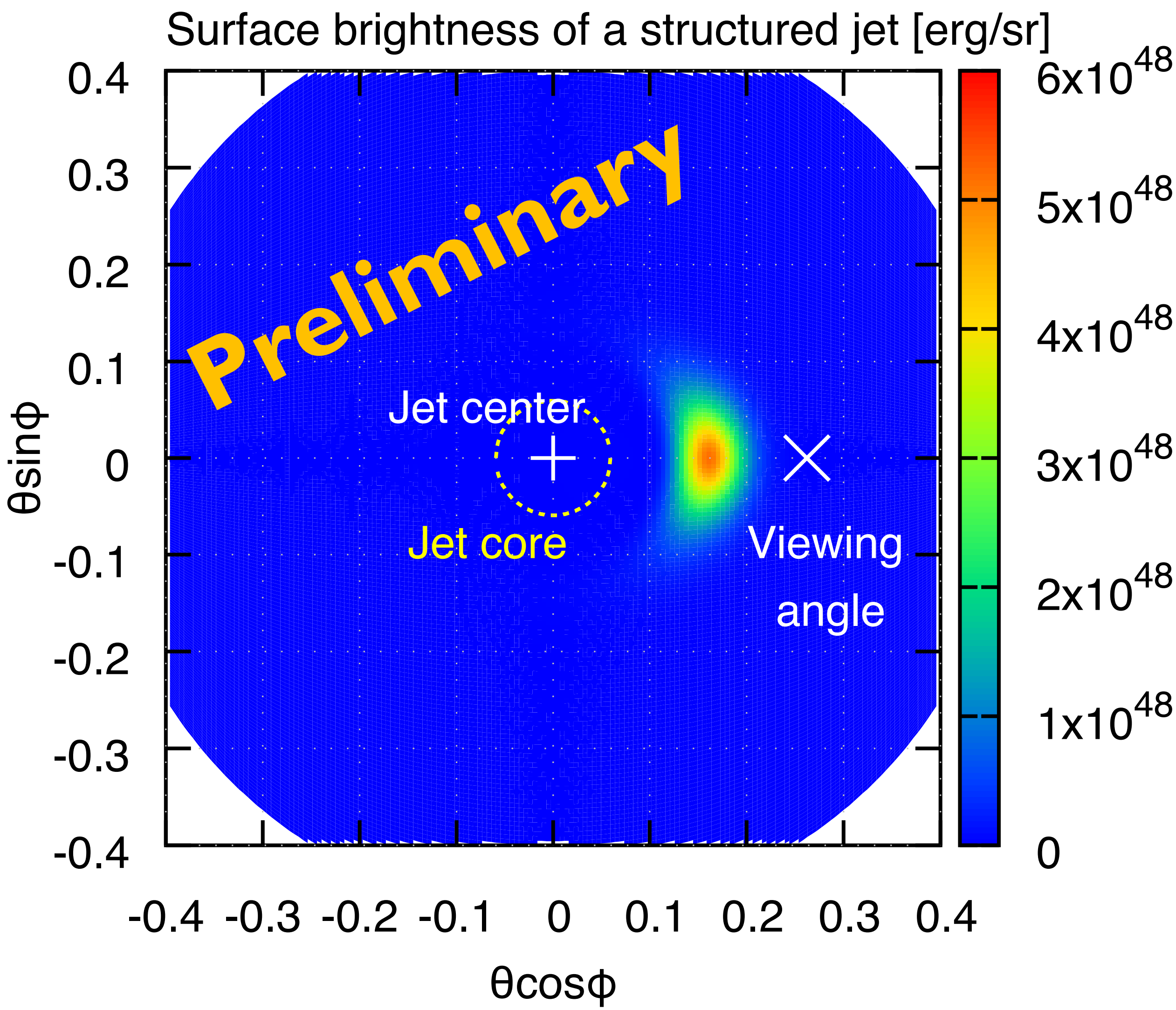
Wide angle

$$\Delta\theta_{sc} \approx \frac{1}{\Gamma_c}.$$

Kisaka+ 17

Kisaka+ 15

Surface Brightness



$$E_{\gamma,\rm iso} = \int \frac{d\Omega}{4\pi} \frac{E_\gamma(\theta)}{\Gamma^4(1-\beta\cos\theta_\Delta)^3}$$

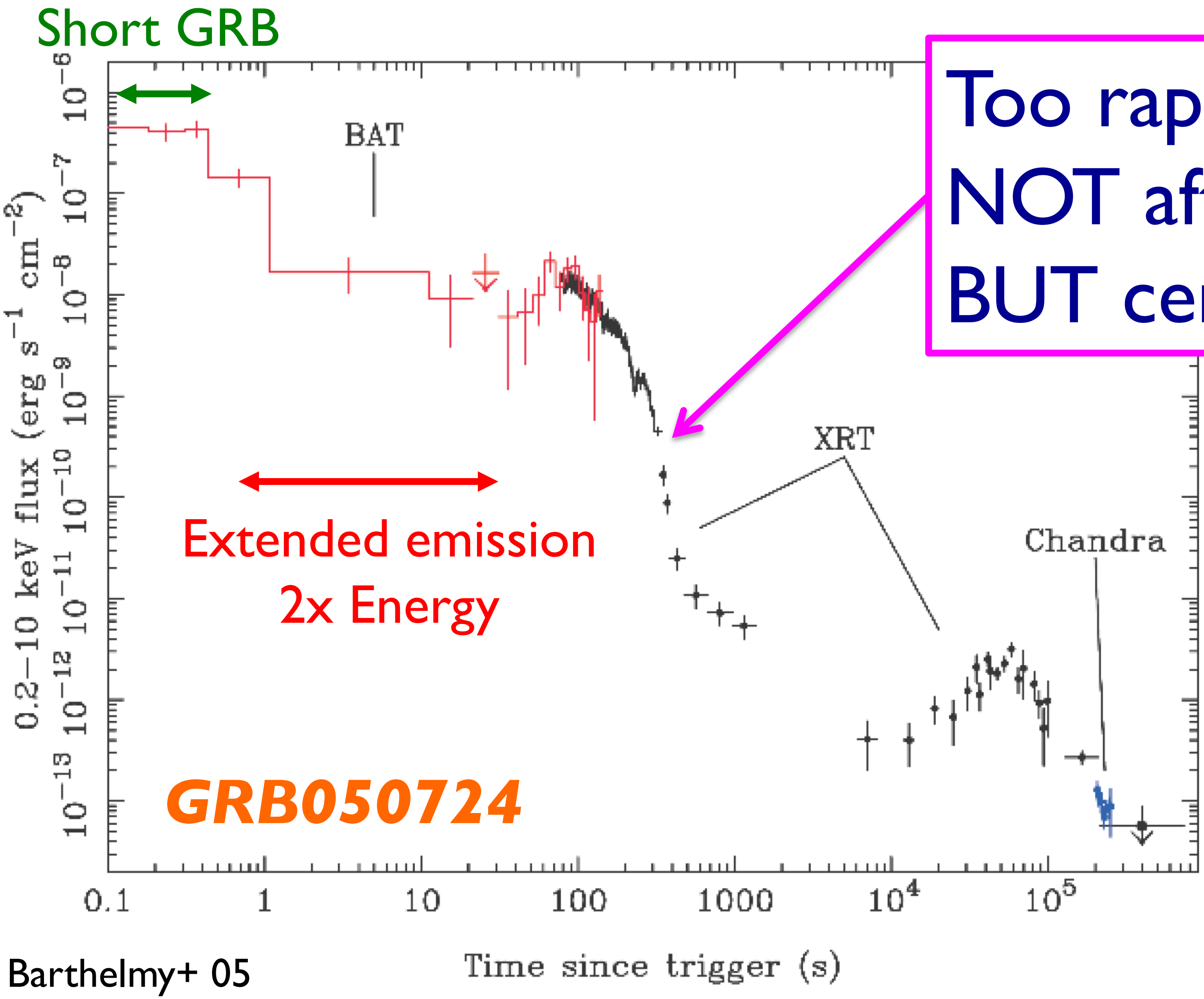
$$\cos\theta_\Delta = \sin\theta\cos\phi\sin\theta_v + \cos\theta\cos\theta_v$$

Most emission comes from the jet edge outside the core & not on the viewing angle

High Energy γ-Ray?

- ***Jet & Afterglow***
  - Extended & plateau emission to $\sim 10^{4\text{-}5}$ sec
  - Off-axis de-beaming
- ***Central remnant***
  - Magnetar
- ***Merger ejecta***
  - Energy injection from central engine?

Short GRBs are Not Short



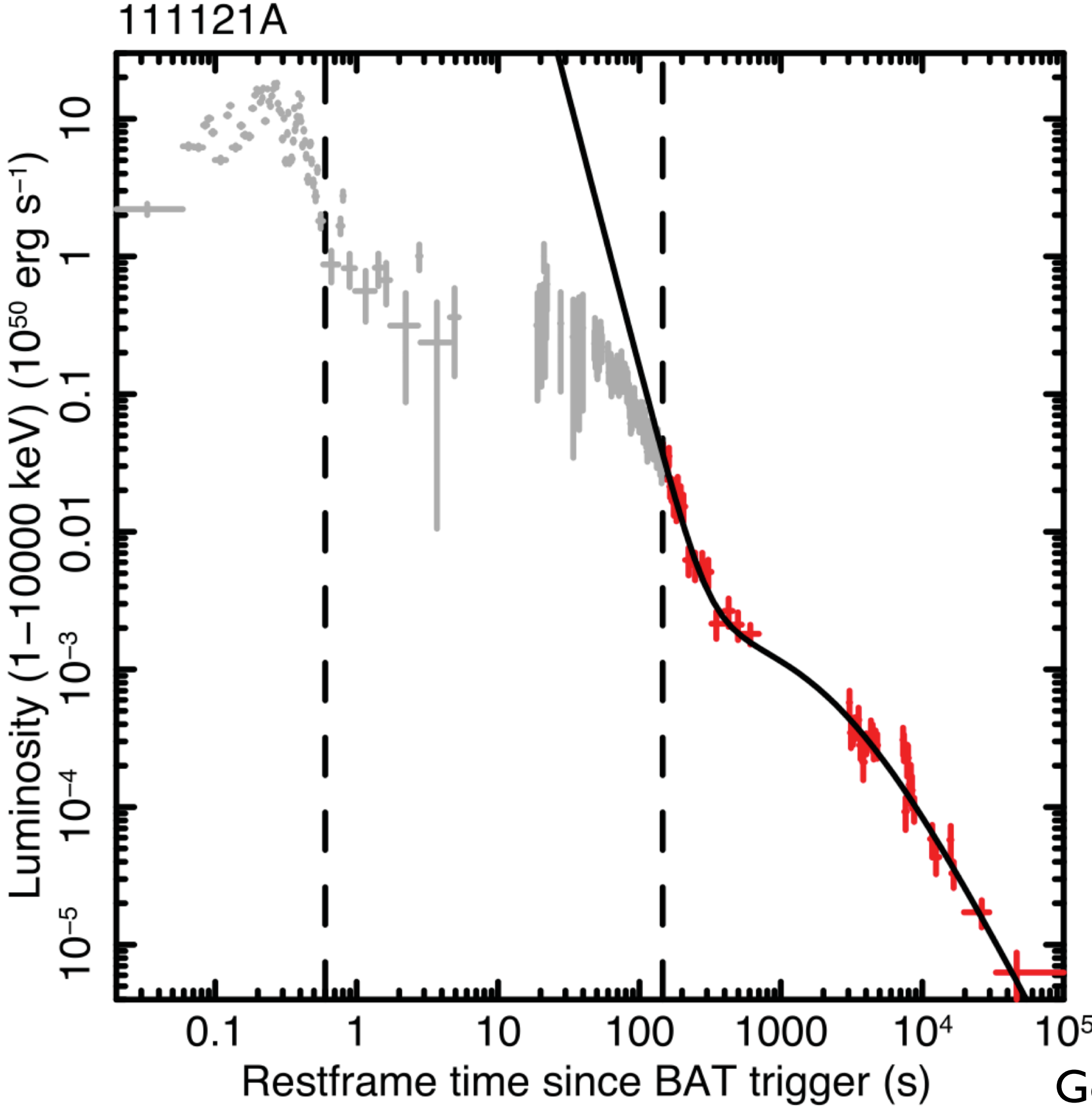
Too rapid decline:
NOT afterglow
BUT central engine

~100 s >> t_{vis} ~ 0.1 s

⇒ Fallback to BH? or Magnetar?

Barthelmy+ 05

Plateau Emission



t ~ 10000 s!

$$\gg t_{\rm acc} \sim \frac{1}{\alpha}\frac{r}{c_s}\frac{r}{h}$$

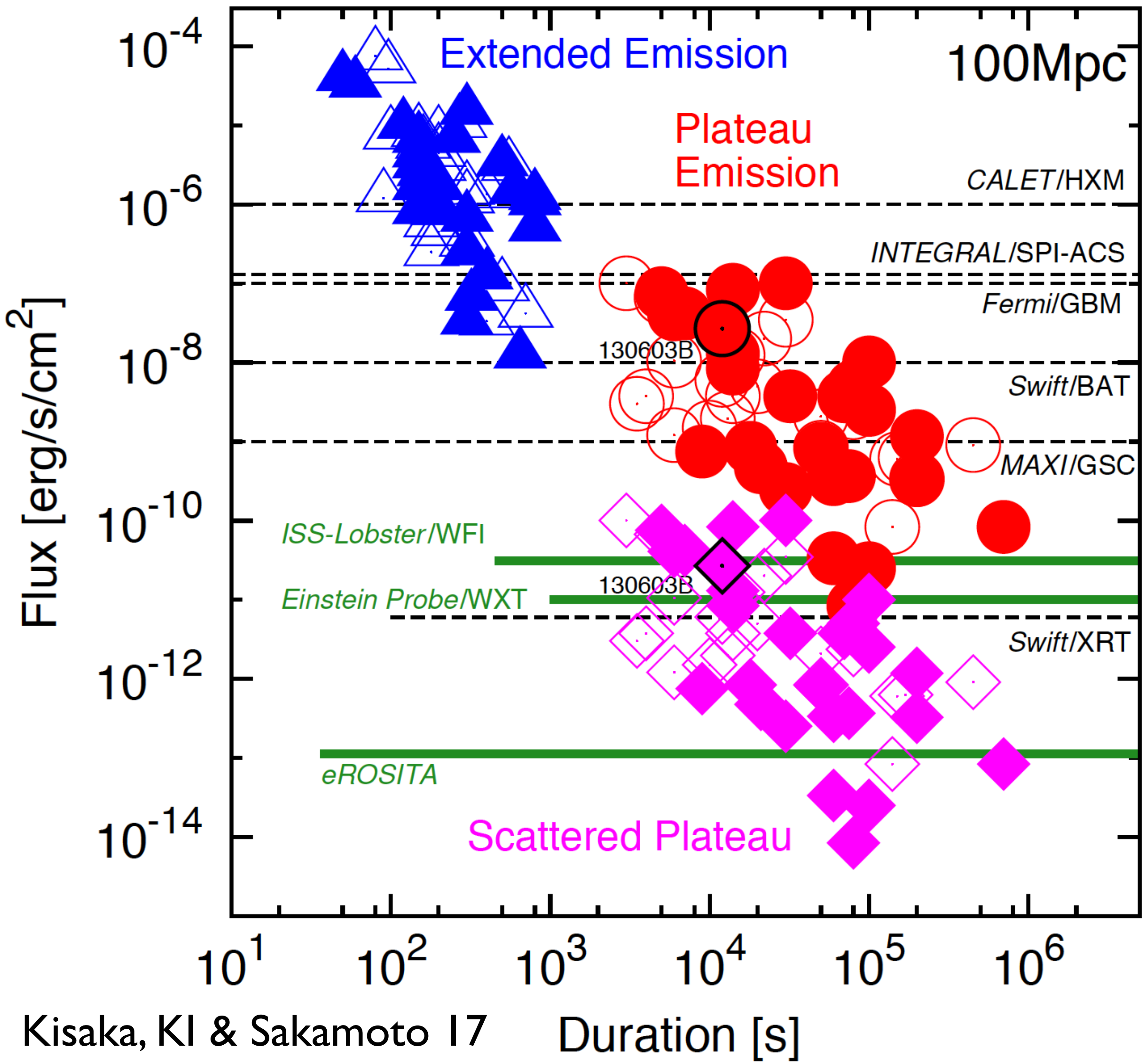
$$\sim 0.1\,{\rm s}\left(\frac{\alpha}{0.1}\right)^{-1}$$

$$\times\left(\frac{r}{10^6\,{\rm cm}}\right)\left(\frac{r}{10h}\right)$$

Fallback? Magnetar?

Gompertz+ 13, 14; Rowlinson+ 13; Li+ 15

EM Counterparts



Kisaka, KI & Sakamoto 17

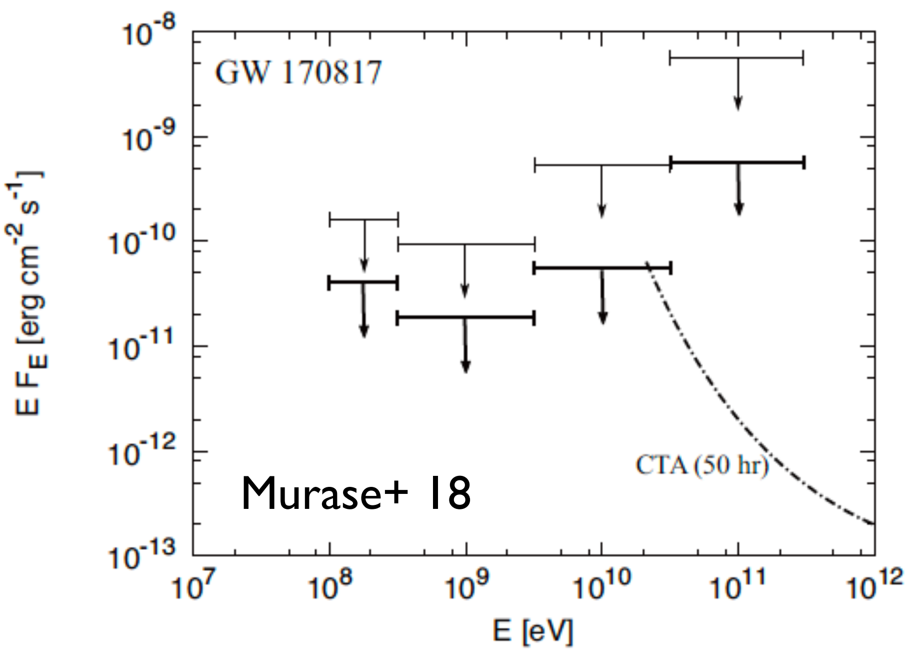
If on-axis & $F_X \sim F_{HE\gamma}$,

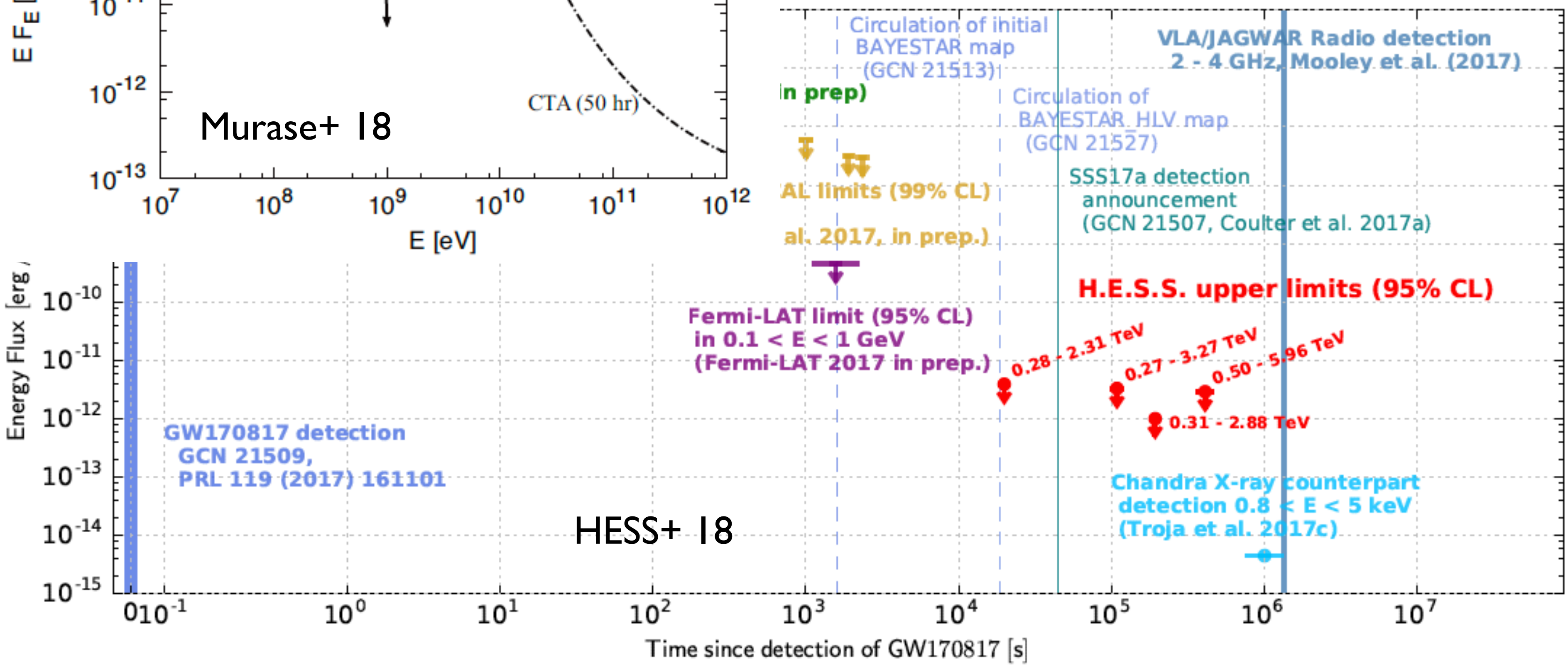
VERY EASY to detect

CTA follow up even no-detect. is important

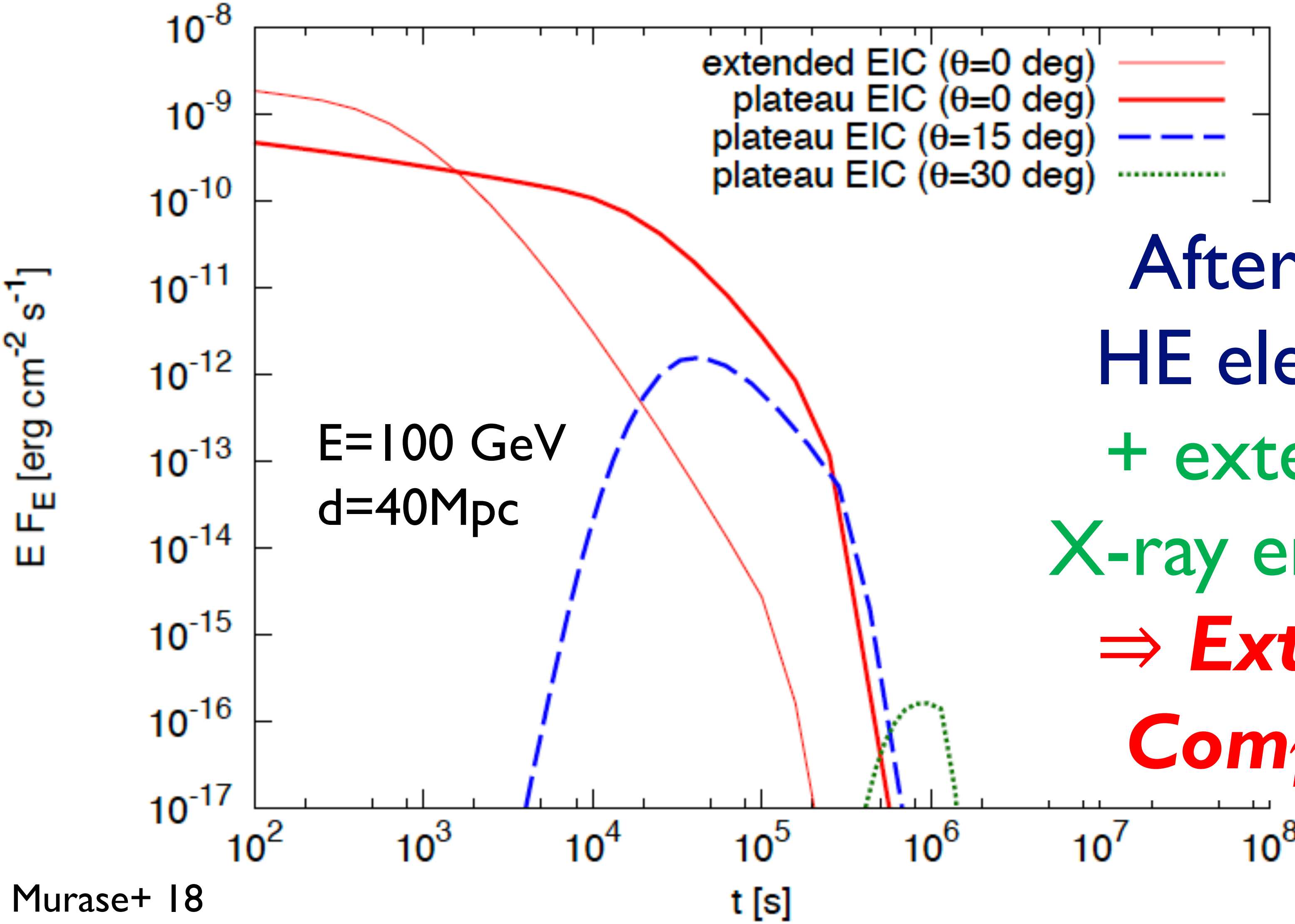
Limits on GW170817

No detection so far
CTA is more powerful





HE γ-ray from Afterglow



Murase+ 18

Afterglow HE electron

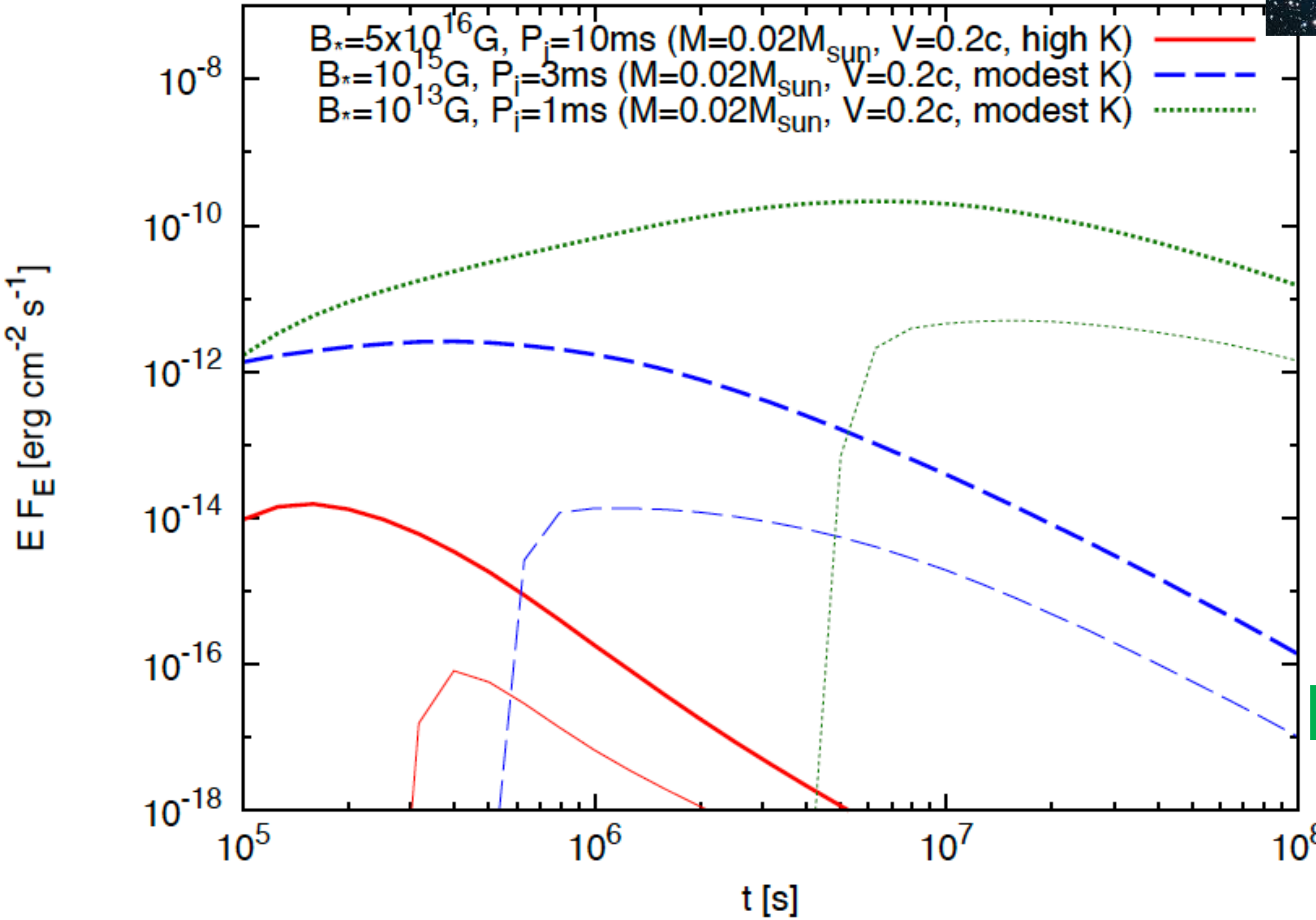
+ extended X-ray emission

⇒ ***External Compton***

High Energy γ-Ray?

- ***Jet & Afterglow***
  - Extended & plateau emission to ~$10^{4\text{-}5}$ sec
  - Off-axis de-beaming
- ***Central remnant***
  - Magnetar
- ***Merger ejecta***
  - Energy injection from central engine?

Magnetar

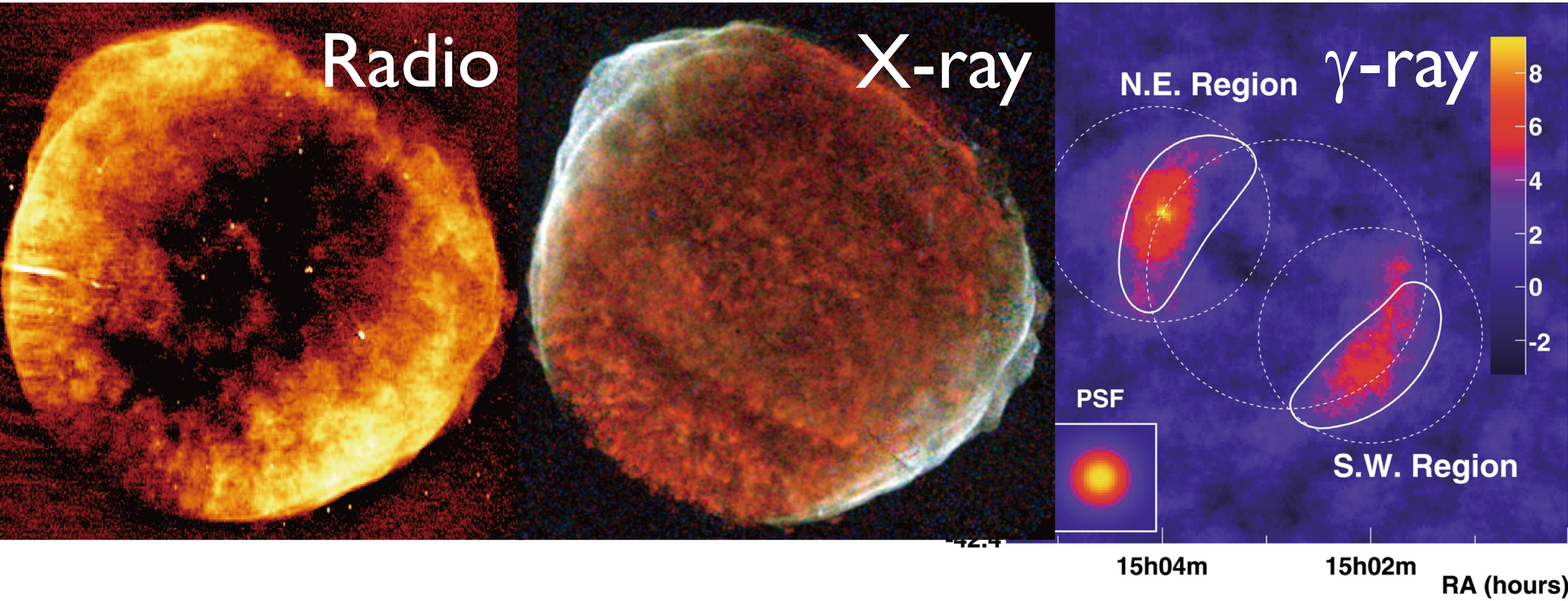


Ejected $M_{NS\text{-}NS} << M_{SN}$

$\Rightarrow \tau < 1$ earlier

Diversity of M_{NS}

Supernova Remnant

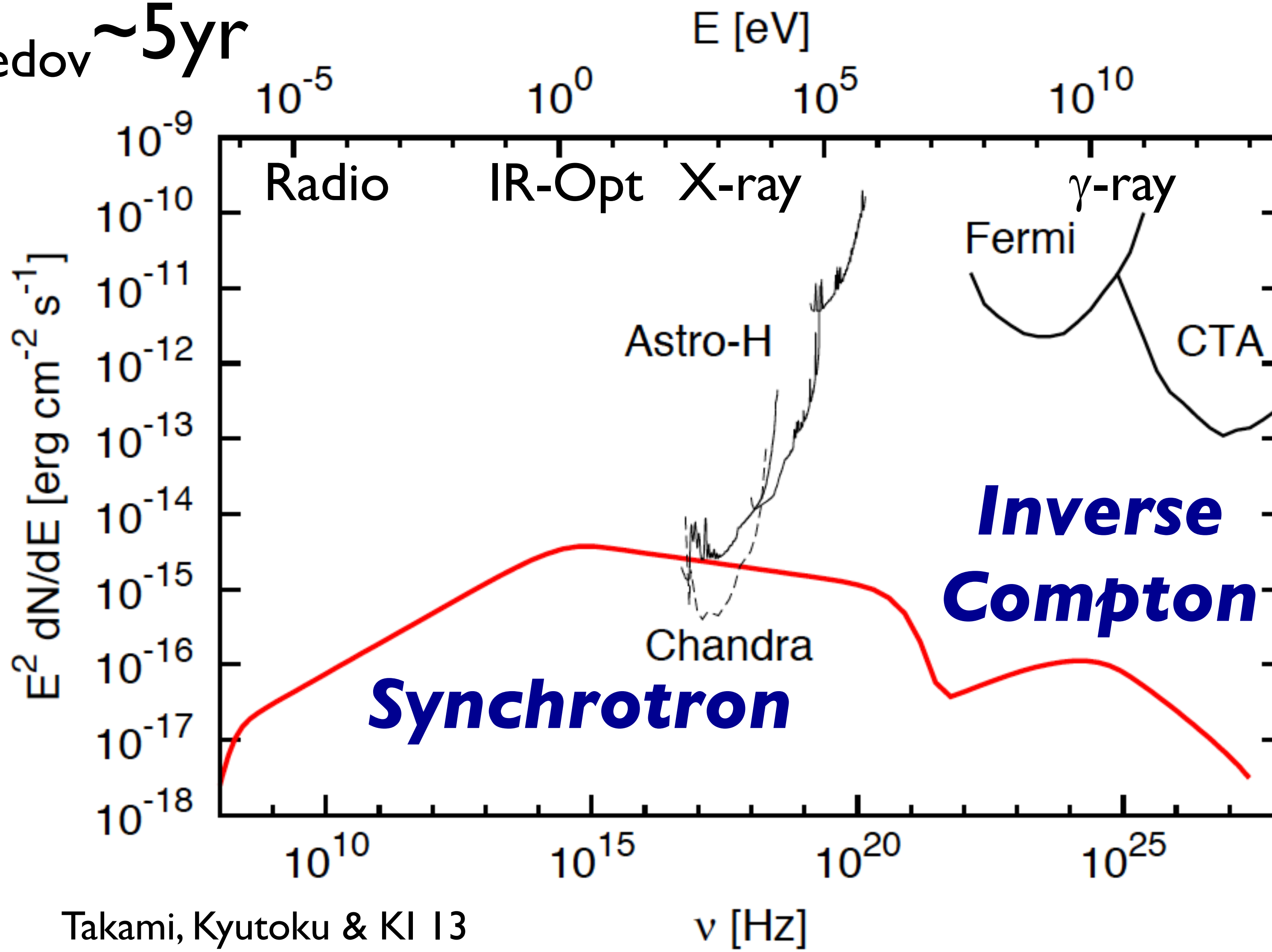


NS merger remnant ~ Supernova remnant

⇒ ***High energy remnant for NS merger?***

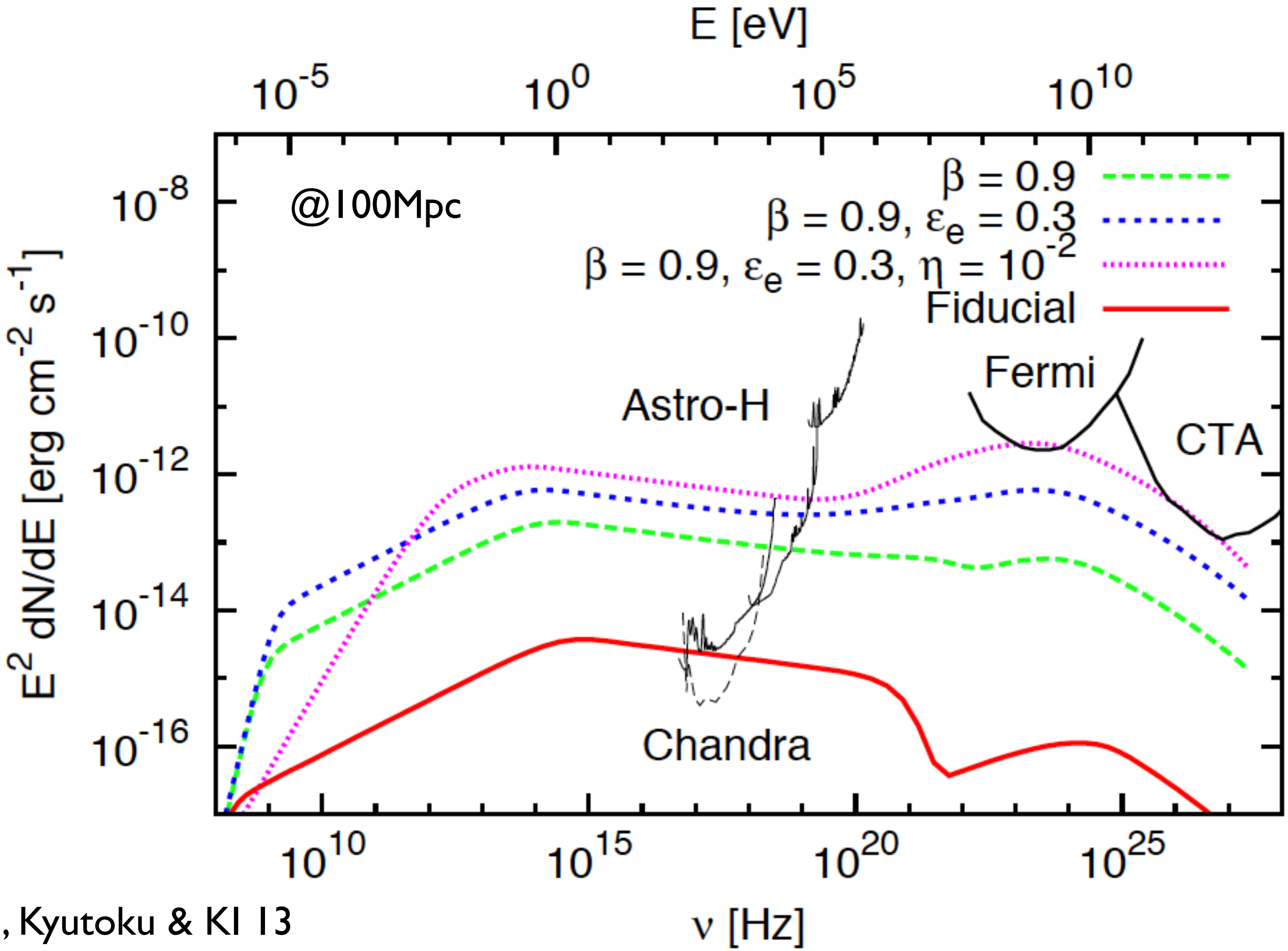
NS Merger Remnant

@t_{Sedov}~5yr

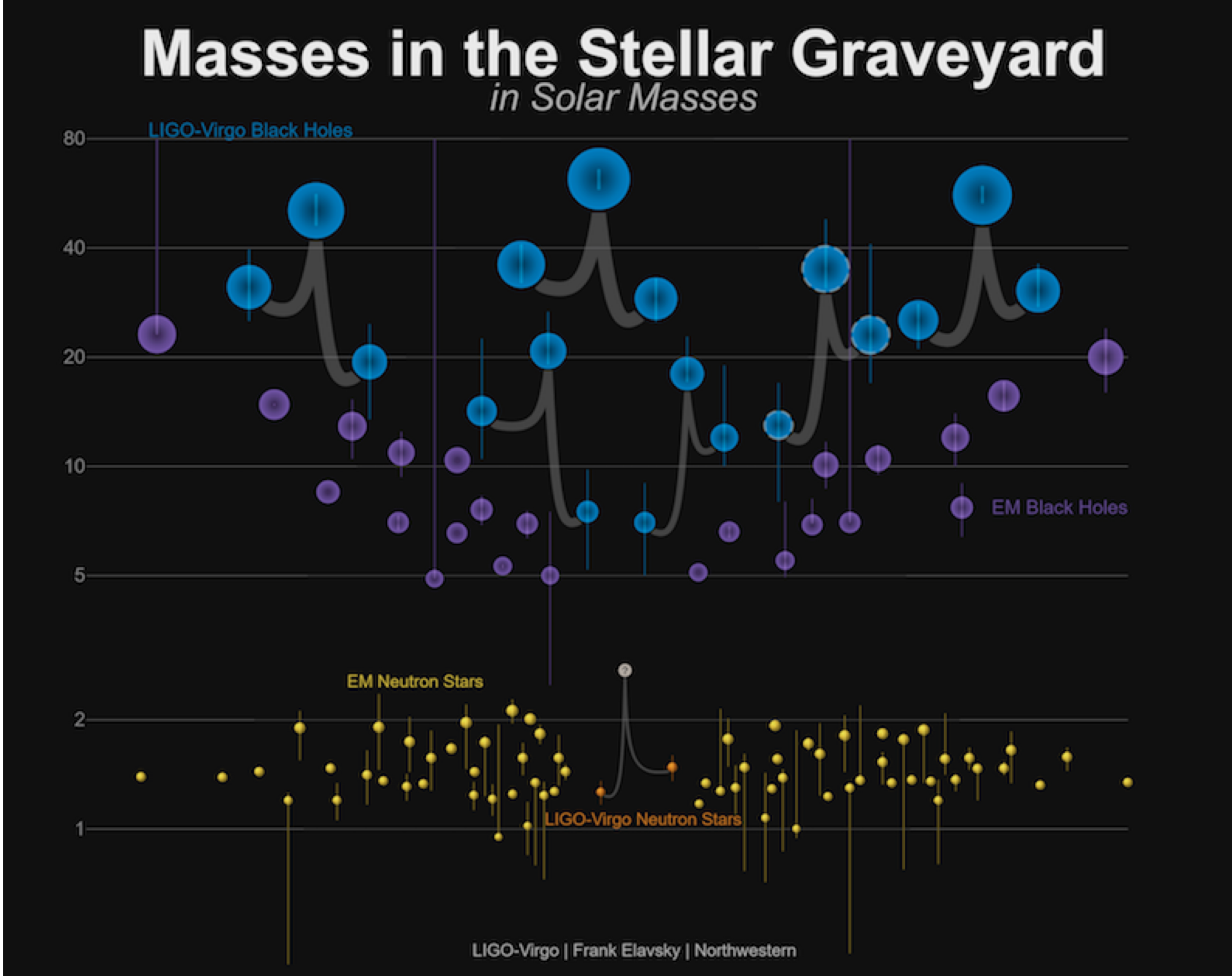


Takami, Kyutoku & KI 13

Merger Remnant Spectrum

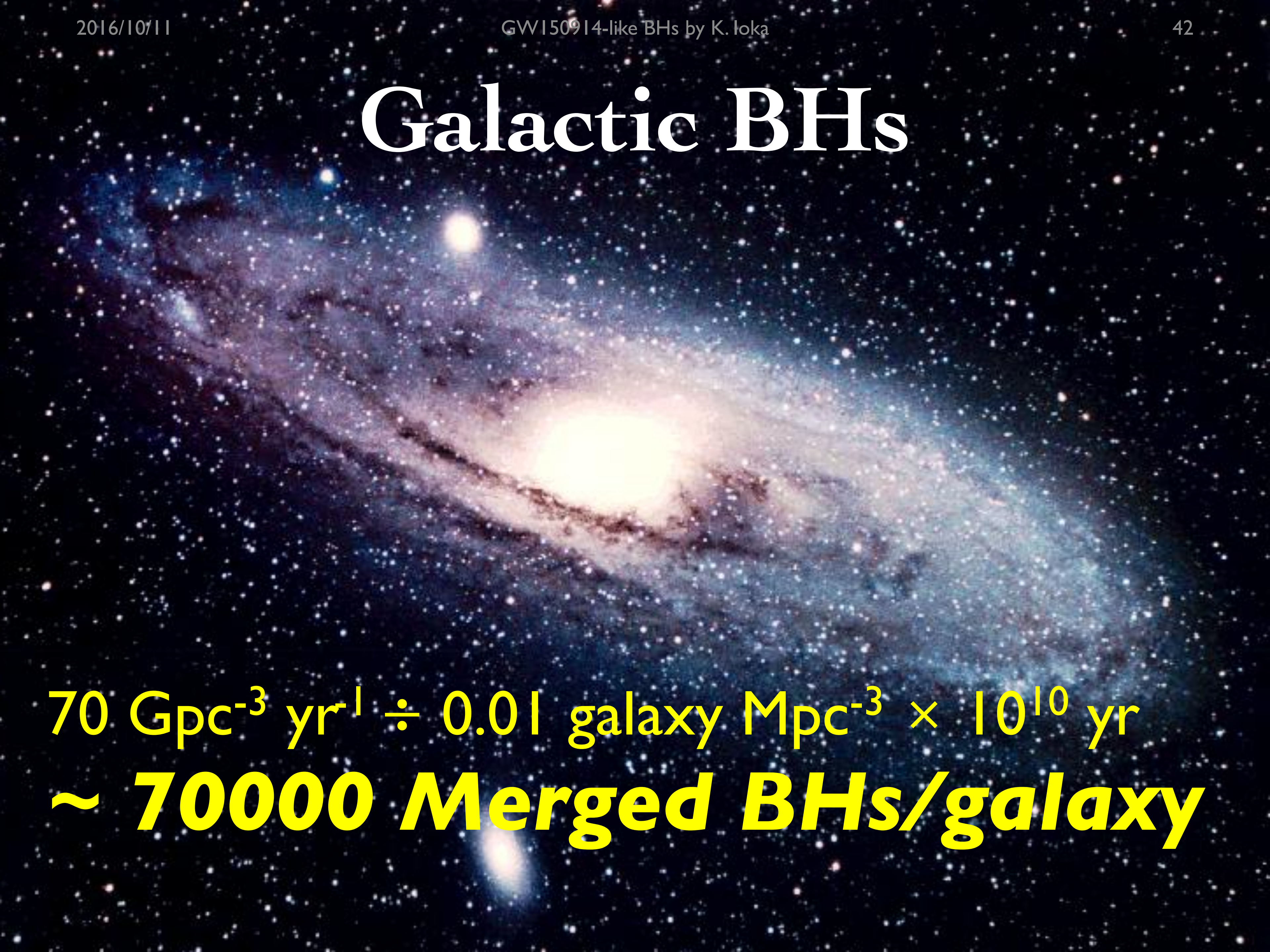


Takami, Kyutoku & KI 13



Masses in the Stellar Graveyard
in Solar Masses
LIGO-Virgo Black Holes
80
40
20
10
5
2
1
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
?
LIGO-Virgo | Frank Elavsky | Northwestern

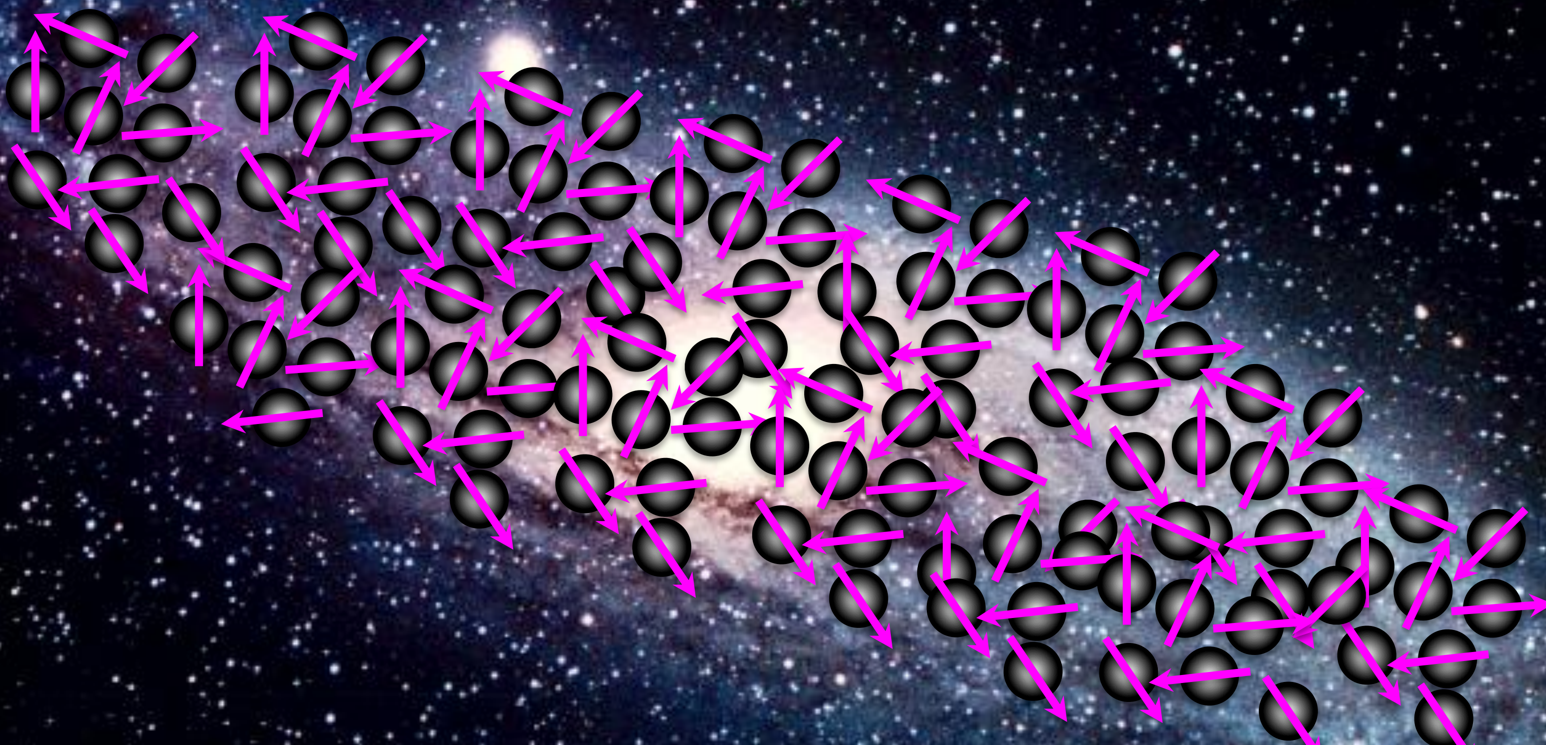
Galactic BHs



70 $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1} \div 0.01$ galaxy $\mathrm{Mpc}^{-3} \times 10^{10}$ yr

~ 70000 Merged BHs/galaxy

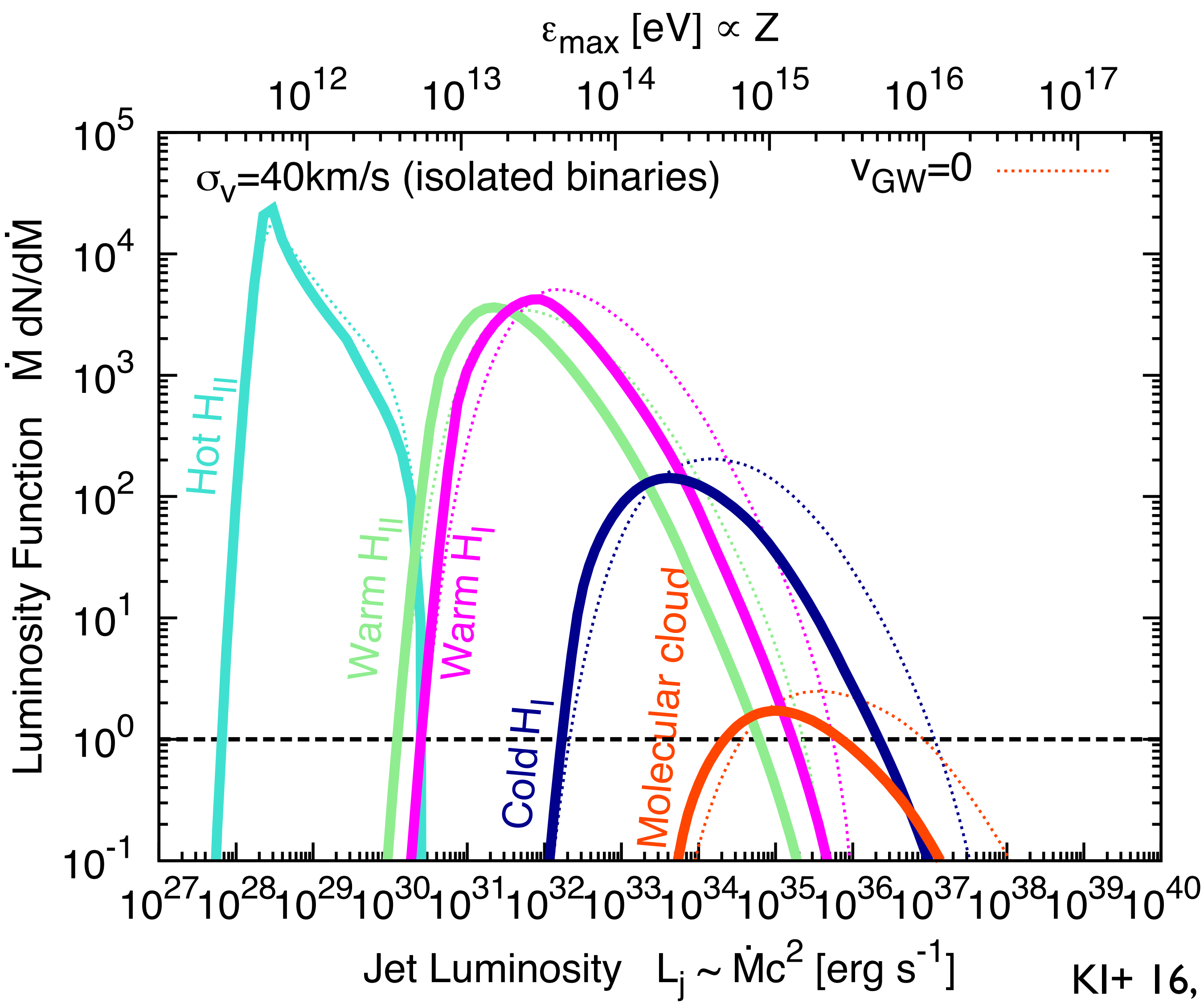
Galactic BHs



$70\ \mathrm{Gpc^{-3}\ yr^{-1}} \div 0.01\ \mathrm{galaxy\ Mpc^{-3}} \times 10^{10}\ \mathrm{yr}$

~ 70000 Merged BHs/galaxy

Luminosity Function

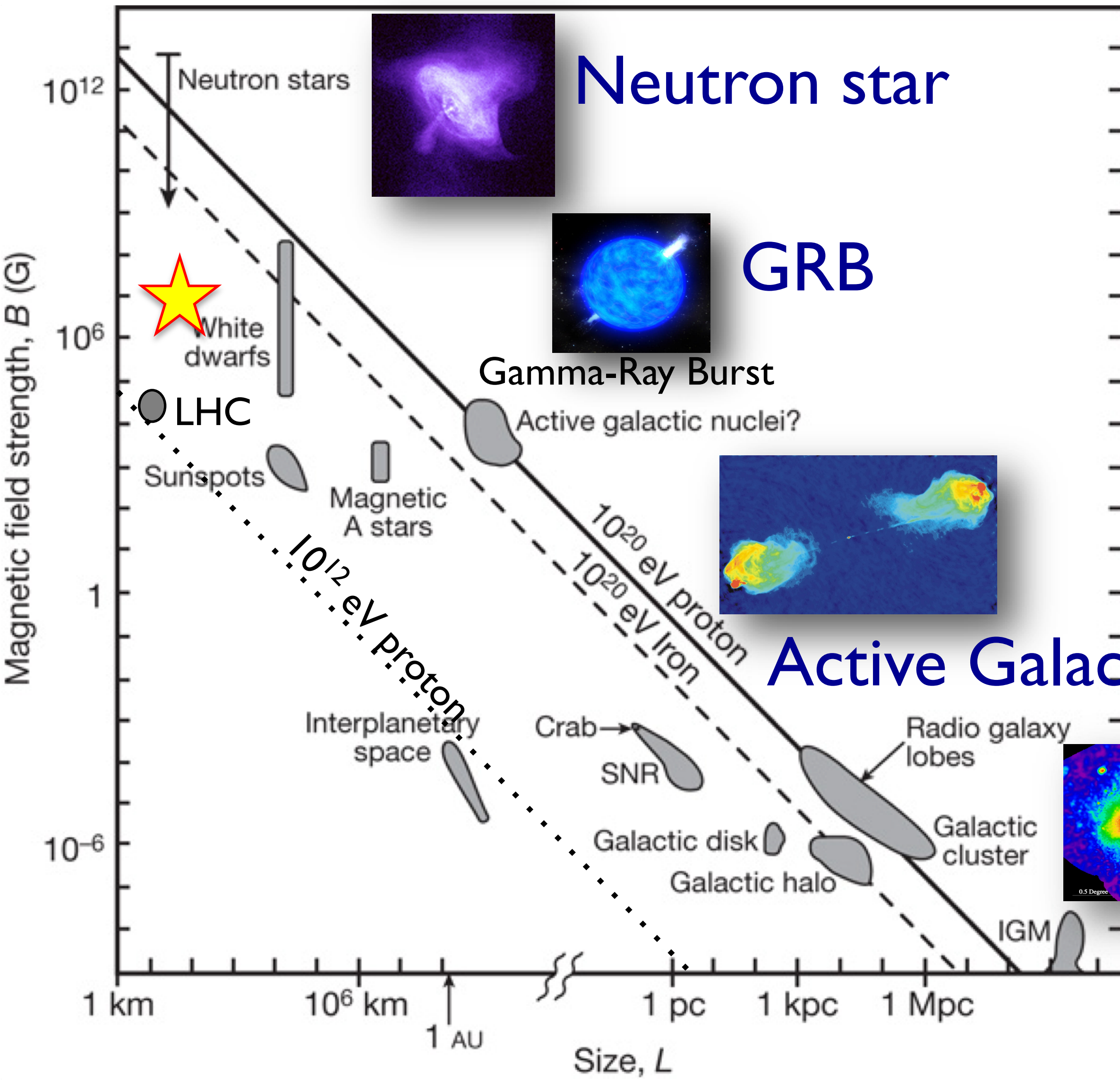


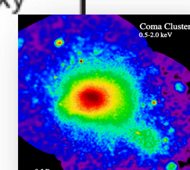
The most luminous BH jet is $\sim 10^{36}$ erg/s in cold H_I

v_{GW} reduces L_j by ~10

KI+ 16, see also Tsuna+18

Particle Acceleration





Galaxy Cluster

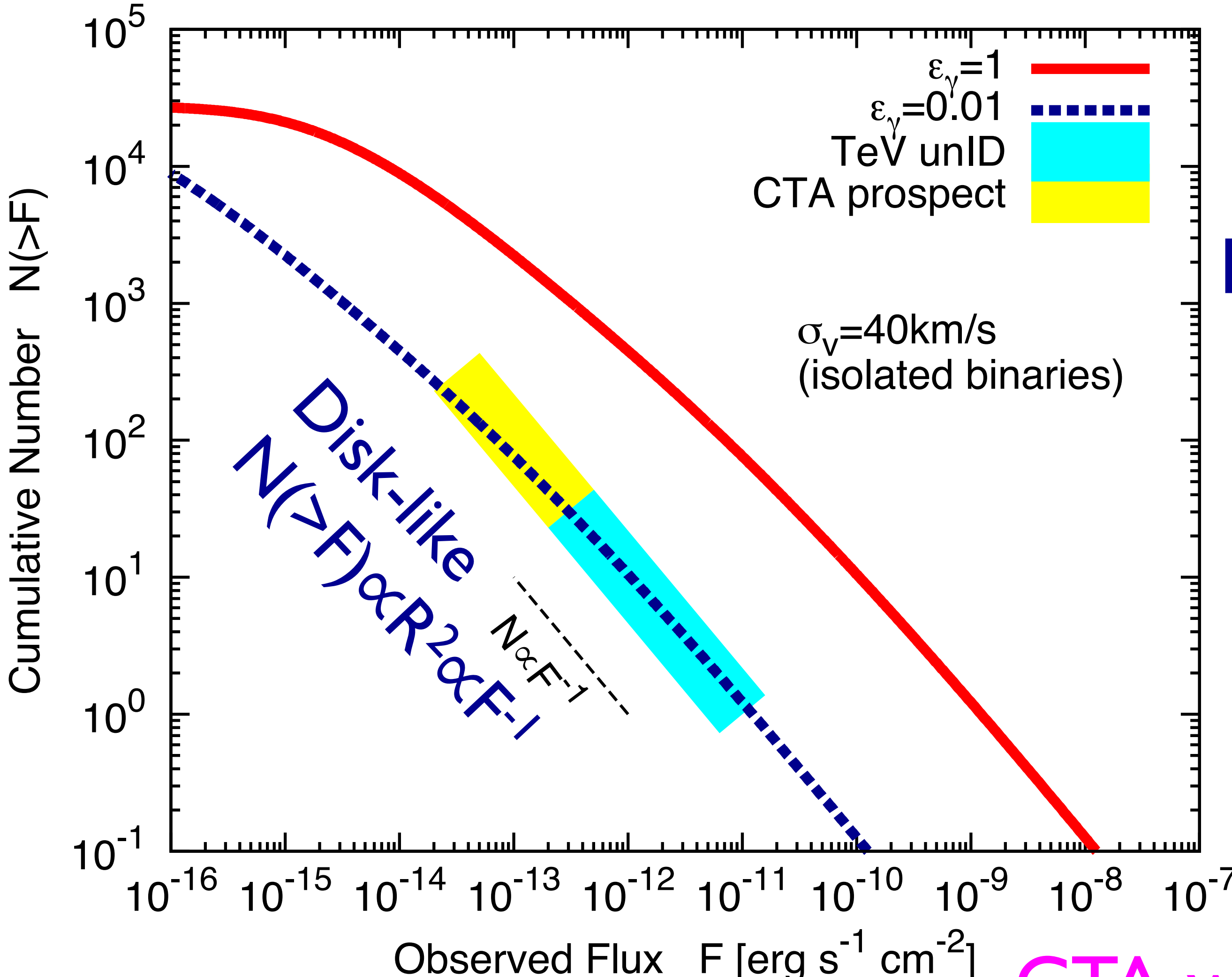
- Hillas condition
  E<ZqBR
- $L_B \sim 4\pi R^2 (B^2/8\pi) c$
  $\propto (BR)^2$
- E_{max}>PeV Blandford 00 Waxman 04

PeVatron!!!

Barkov+ 12
KI+ 16

Dark Matter?

Log N – Log F



KI+ 16

BHs ⇔ TeV unIDs?

Flux dis. is similar

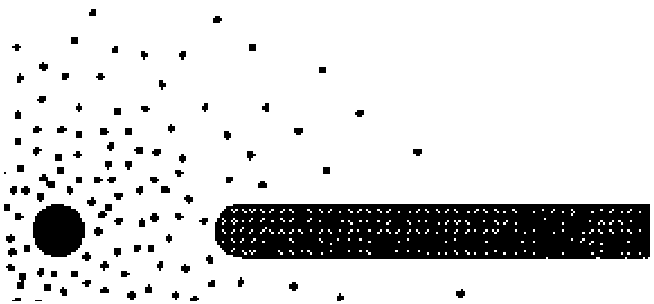
BH nebula size:

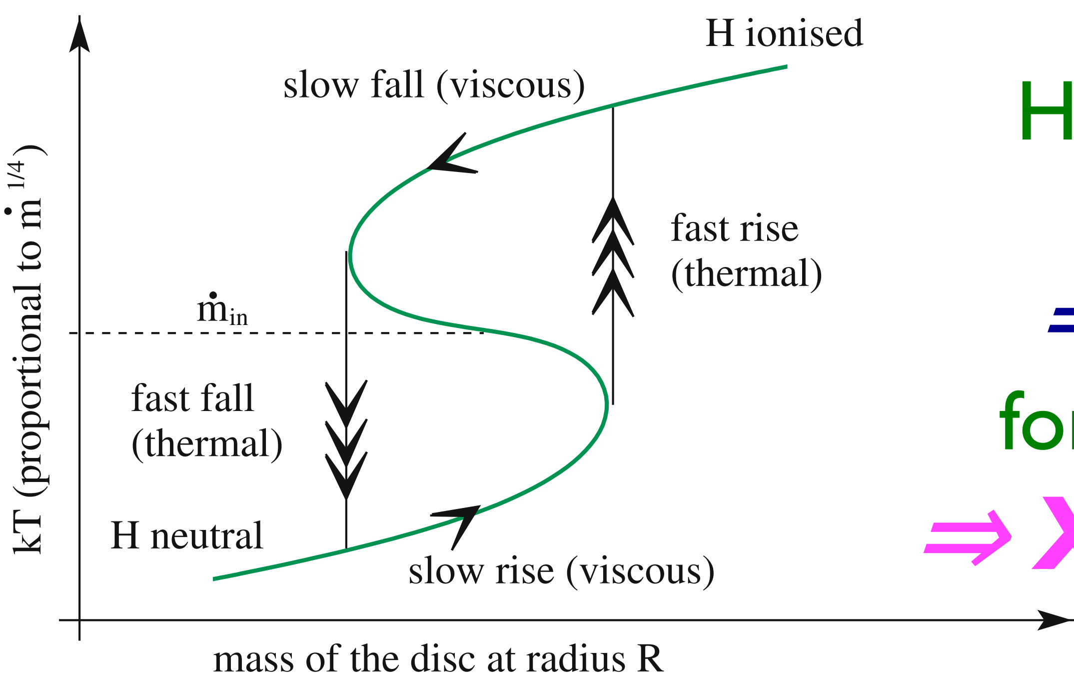
$$\frac{L_j}{4\pi r_h^2 \theta^2 c} \sim \rho V^2$$

$$\Rightarrow \quad r_h \sim 3 \text{ pc}$$

CTA will see ~300 BHs

X-ray Nova?





Hydrogen-ionization disk instability

ADAF + Standard disk

Outer disk is cold

Hydrogen recombines

H^- ion opacity

⇒ S-shaped curve

for thermal equilibrium

⇒ X-ray nova-like?

Matsumoto+ 17

Summary

- ***sGRB170817 & GRB 170817A***
  - Off-axis jet
  - Jet structure?, Spectrum?, Mechanism?
- ***High energy γ-ray for CTA***
  - Jet, Afterglow, Magnetar, Merger ejecta
  - ***CTA follow-up is important***
- ***BH remnant in our Galaxy***
  - Some TeV unIDs? X-ray novae?

Thank You